PHD

Design for Verification

A Metrology Based Design Framework to Aid Right First Time Assembly for Large Volume Aerospace Structures

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Award date:
2017

Awarding institution:
University of Bath

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A Metrology Based Design Framework to Aid Right First Time Assembly for Large Volume Aerospace Structures

Submitted by

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for the degree of Doctor of Philosophy

of the

University of Bath

Department of Mechanical Engineering

April 2017

Acknowledgements

I would firstly like to thank Prof Paul Maropoulos for providing the opportunity to undertake this PhD and for whom without, this would have not been possible. It was a privilege to have worked for you and I am ever grateful for everything I learnt along the way. I would also like to thank my now supervisors Prof Glen Mullineux, Prof Patrick Keogh and Prof Chris Bowen for their steady direction and helping convert my ramblings into something coherent. Your humour has been a source of encouragement through the obstacles faced during the writing of this document.

I am indebted to the team at Airbus Defence and Space, most notably Kevin Clynes, Margaret Fowler and Jason Scott, who coached me in spacecraft manufacturing and provided invaluable support. You made the journey interesting and enjoyable whilst welcoming me into your team during the weeks I spent in Stevenage.

My appreciation goes to Andy Portsmore and John Watton of GKN Aerospace for their generosity and attentiveness during my time of write-up, this would not have been possible without your support.

Finally, I'd like to thank my wife, Alison. Your caring nature and unfailing support has kept me afloat. I couldn't have done this without the constant flow of food and drink you lovingly supply as I perpetually forget to eat and drink whilst working on computer code.

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Nomenclature

(ADM)	Absolute Distance Measurement
(AEM)	Assembly Evaluation Method
(AIT)	Assembly, Integration and Test Facility
(BMR)	Bearing Mounted Retro-reflector
(CFRP)	Carbon Fibre Reinforced Plastic
(CM)	Communications Module
(DfA)	Design for Assembly
(DfM)	Design for Manufacture
(DfMA)	Design for Manufacture and Assembly
(DFSS)	Design for Six Sigma
(DfV)	Design for Verification
(DfX)	Design for 'X' or 'Excellence'
(EADS)	European Aeronautic Defence and Space
(ESA)	European Space Agency
(FAL)	Final Assembly Line
(GPS)	Geometric Product Specification
(GUM)	Guide to the Expression of Measurement Uncertainty
(IAL)	Integrated Assembly Line
(IFM)	Interferometer
(KCs)	Key Characteristics
(LOS)	Line of Sight
(LVA)	Launch Vehicle Attachment
(MAA)	Measurement Assisted Assembly
(MAC)	Main Assembly Cell
(MAF)	Main Assembly Fixture
(MASC)	Main Assembly Super Cell
(MCS)	Monte Carlo Simulation
(MDO)	Multidisciplinary Design Optimisation
(MoD)	Ministry of Defence
(MPE)	Maximum Permissible Error
(MSA)	Measurement Systems Analysis
(NDT)	Non-Destructive Test
(NPD)	New Product Development
(NPL)	National Physical Laboratory
(PDF)	Probability Density Function
(PDP)	Product Design Process
(PLM)	Product Lifecycle Management
(PUMA)	Procedure for Uncertainty Management
(RFT)	Right First Time
(RMS)	Root Mean Squared

(RSS)	Root Sum Square
(SM)	Service Module
(SMR)	Spherically Mounted Retro-reflector
(SoA)	State of the Art
(TRL)	Technology Readiness Levels
(VLT)	Virtual Laser Tracker

Abstract

Large volume processes within the aerospace industry, such as final wing build or telecommunications spacecraft integration, are commonly at the mercy of challenging assembly tolerances that require modern metrology instruments to be successfully realised. Holistic capability models for widely used instruments such as the laser tracker and photogrammetry systems are not currently utilised within the early stage design phases to aid tolerance design. The goal of the work presented within this thesis was to create, test and prove a set of design guidelines for the aerospace industry titled 'Design for Verification' that consider estimated measurement uncertainty within the early design stages when there is a lack of historical data to adequately inform simulation based design. The guidelines were created to inform design engineers within low rate, high value manufacturing industries, where process capability data are unattainable, to set realistic and achievable tolerances whereby ensuring product conformance and measurability. This was achieved by introducing an additional parameter to the widely established Design for X toolbox, Design for Verification. The focus of Design for Verification is primarily upon the use of metrology and how it impacts large volume assemblies in modern aerospace manufacturing. The Design for Verification guidelines were created with the key objectives of promoting assembly process optimisation, product conformance and reduced cost. The DfV guidelines were applied to an existing product, detailing existing processes in order to baseline a process for comparing the guidelines against. The DfV guidelines were then applied to the same product to demonstrate how they should be used within the early design phase and the results of before and after implementation of the guidelines were compared. A physical demonstrator was designed around the existing Eurostar 3000 telecommunications satellite platform, from Airbus Defence and Space, to test the proposals and design changes derived through following the Design for Verification guidelines. Application of the Design for Verification guidelines resulted in: reduced measurement uncertainty, optimised assembly sequencing, improved tooling design, informed tolerance synthesis and analysis and advanced metrology processes. This has resulted in direct cost benefits for the Airbus Defence and Space telecommunications platform with an estimated saving of 20% for the next generation NEOSAT spacecraft.

Chapter 1

Introduction

1.1. Scope

Design for X (DfX) encompasses a broad range of both specific and generalised guidelines to aid designers in meeting predefined design objectives. The purpose of DfX is to cost effectively achieve an optimal final product and work towards Design for Six Sigma (DfSS) [1]. DfSS is used to eliminate design vulnerabilities by ensuring all functional requirements of a product's geometry can be maintained at plus or minus six times the standard deviation for each component. This design process has proven to ensure confidence in end product conformity with minimal costs incurred. Whilst this previous statement remains true for a majority of modern manufacturing requirements, industrial collaborations have shown that it is yet to be realised within the aerospace industry for large component assembly. This is largely due to a requirement for tight assembly tolerances across large volumes (more than 1m).

Aerospace tolerances create engineering challenges, often only tackled during latter stages of production through the use of undesirable shimming and or fettling of critical assembly interfaces. This is also true within the assembly of the Airbus Defence and Space Eurostar 3000. The majority of this thesis focuses on the design and build process for the Eurostar 3000 and proves the effectiveness of applying the author's proposed process, Design for Verification, in order to meet critical assembly tolerances first time to ensure right-first-time (RFT) [2] manufacture for large component assembly [1].

DfX guidelines that reside within the overall DfSS theory are divided into four subcategories for the phases apparent within a product life cycle. These phases are summarised as:

1. Development phase
2. Production phase

3. Utilisation phase
4. Disposal phase

Within aerospace, these design phases are often approached separately during early stage development. This is due to engineers often specialising within a single field or discipline. Design for Verification (DfV) is a concept which spans across the first two phases to close a knowledge gap observed through industrial collaborations. These observations are further explored within the case studies found in Chapter 3. The primary necessity for DfV is to enable early stage estimation of product conformance to guide assembly design processes. DfV is based upon measurement uncertainty estimation and modelling to guide methods for final assembly processes and tooling design, tolerance allocation and verification processes.

1.2. Motivation

With the continual increase of knowledge within engineering and the advancing global requirement for enhanced technologies, commercial competition is driving a forced reduction in product and production costs [3]. This is placing strain upon production design engineers to develop and optimise flexible and reactive systems to cost effectively adapt product designs for ranging customer requirements within increasingly tighter time constraints. Design adaptability, reusability and the capability to rapidly develop products and services for the e-commerce era are key areas of interest within high value manufacturing industries as they are viewed as essential to maintain sustainable growth [3]. One example of this is the steady rise in commercially available spacecraft, which, due to the high cost and limited availability of knowledge and technology, was once limited to government funded bodies. The rise in global interest for space travel and exploration has opened up the market to private companies, introducing increased levels of competition, forcing government funded spacecraft manufacturers to drive down cost and improve product functionality, aesthetics and efficiency, where previously, the thought of market competition was unheard of [4].

Rising interest in space travel and increase of knowledge has placed and continues to place increased pressure upon spacecraft manufacturers, hence creating pathways and opportunities for competing bodies to enter into market. Historically, the space industry was only accessible through Government funded institutions in what was termed as the “space race”, dominated by Russia and America [5], [6]. Only within the past decade has the world seen such a rapid increase of available and affordable space technology for the public with numerous countries now involved in space exploration with the ultimate aim of human space travel beyond the moon [7]. This has in turn created larger scope for competition as market diversity increased and customers gained increased choice opportunity.

Market competition has created a necessity for designers and production engineers to develop novel methods for spacecraft production in order to maintain rigorous standards of quality whilst significantly reducing costs and lead times. Although cost is currently a significant factor driving the requirements for change, customers are becoming more demanding in their desires for customisation. Product customisation is forcing designers to introduce modular build systems with cost effective customisation to best suit individual customer needs. Furthermore, this is placing increased strain upon production processes to keep up with customer requirements which is unsustainable using current manufacturing methods. The DfV proposal presented was created through a requirement from Airbus Defence and Space (ADS) - Stevenage, a UK based spacecraft manufacturing facility, to design and build satellite platforms with reduced cost and increased confidence in end-product conformance. The author worked collaboratively with ADS to achieve this, and in so doing, established novel design proposals and production approaches to save cost and increase production potential.

1.3. Need

The Eurostar 3000 is the Airbus Defence and Space current flagship spacecraft platform for military and public telecommunications. The first of the Eurostar series, the Eurostar 1000 model, was launched in 1990, Inmarsat-2 F1, it was de-orbited after 22 years of service [8]. The success of Inmarsat-2 F1 spearheaded the success of the Eurostar model to become the satellite of choice for the United Kingdom’s Ministry of Defence (MoD) as a baseline platform for defence communications, along with many other telecommunications service providers. It remains the spacecraft of choice for the MoD and is currently the platform for the Skynet 5 system [9].

Although the Eurostar design went through a number of iterations, the overall structural characteristics of the spacecraft did not significantly change. The assembly, tooling, tolerancing and metrology procedures were also largely unchanged throughout the structural design iterations, largely due to the highly celebrated success of Inmarsat-2 F1, which admittedly led to the creation of a culture and ideology of - if it’s not broken, don’t fix it. This too was coupled with a reluctance in altering a proven process. It was not until emerging organisation such as SpaceX claimed a mission of pushing ADS out of the market through their low-cost, privately funded space innovations that drove a requirement within the space industry to redesign their production manufacturing model [5]. For this reason, ADS were required to reconsider every manufacturing process in the production of the Eurostar 3000 including the structural design itself. The European Space Agency (ESA) funded an international programme to revise the design and manufacturing processes for the Eurostar 3000 which at the time of writing, is still under-way. The challenge of implementing widespread design change for significant structural and assembly processes became apparent. The next generation E3000 design is named NEOSAT to highlight the advances from the predecessor.

Due to rapidly advancing technologies across multiple industries, a method to effectively guide designers within the aerospace industry to design large volume structures with the latest tooling and metrology technologies available did not exist. It was through this program that the author created, tested, refined and proved the DfV guidelines which have been created for use within any low volume high value aerospace structure manufacturing design facility.

Early design rules need to be founded upon a knowledge of the environment in which the product is to be manufactured so as to optimise the metrology and assembly processes to suit. The capability to engineer aerospace structures with embedded key assembly features based upon metrology system characteristics, which would in turn promote alternative methods for tolerancing, assembly and associated tooling configurations, would enable manufacturers to significantly optimise structural design for improved product conformance with reduced timescales and costs. This would ultimately be achieved through closing the knowledge gap between sequential sectors within design, manufacture, assembly and integration in order to improve RFT manufacturing capability.

It is well attested that there is a need to implement intelligent design rules for successful product assembly, integration and verification in the early stages of product development. It is essential that clear streams of communication should be established between design and production sectors to improve RFT manufacturing. It is estimated that RFT manufacturing currently has a success rate between 60%-70% [10] within high value low volume engineering, which further emphasises the need to introduce early stage product and process design guidelines to ensure RFT manufacturing.

The rationale behind the research was primarily to reduce UK spacecraft manufacturing costs. It was to establish methods to enable design engineers to produce optimal products and processes without compromising quality whereby reducing cost with an added aim of improving RFT statistics. The results of this research have the potential to promote significant manufacturing cost reductions, increasing competitiveness within the aerospace industry and significantly reducing waste through minimising failures. This in turn will act as an enabling pathway to provide affordable services, previously only accessible to governing bodies, for the public at reduced cost and a reduced time to market.

1.4. Aims and Objectives

The primary aim of this research was to create a set of design guidelines, for use by aerospace structure designers, titled DfV, to be created with an intention to complement the existing rules of DfX. The targeted application of DfV is large volume assembly and integration processes (where large volume refers to any assembly or measurement greater than 1m). The DfV guidelines are tested and proved through a design and build demonstrator using the Airbus Defence and Space Eurostar 3000 as a case study in Chapter 6 and Chapter 7.

The secondary aim of this research was to propose methods that assist designers in defining critical tolerances for large volume assemblies, when the defining assembly accuracy is limited by measurement uncertainty. The analysis methods are rooted upon the creation of instrument specification based uncertainty budgets and optimised measurement planning and uncertainty reduction. The data from the estimated uncertainty budgets are used to trade off process criteria against capability and assembly sequencing. The DfV guidelines were designed with seven main objectives to aid in achieving product conformance. The overarching objectives for the proposed successful creation of DfV, are based on the creation of methods to achieve the following:

Objective 1	Metrology instrument specific constrained product design.
Objective 2	Metrology instrument specific constrained tooling design.
Objective 3	Measurement uncertainty informed tolerancing.
Objective 4	Measurement uncertainty constrained assembly tooling design.
Objective 5	Measurement uncertainty constrained process design.
Objective 6	Measurement uncertainty guided assembly sequence design.
Objective 7	Measurement uncertainty guided, verification based design.

1.5. Research Question

The main research goal presented within this thesis is to close an observed knowledge gap between design and production within large volume, aerospace structure design. The research questions posed are:

Primary Research Question

a) Can a single design aid for verification be established within the context of enhancing the Design for X toolbox to enable designers to implement intelligent design rules based upon instrument specific capability and real world scenarios to improve the rates of RFT manufacturing?

Secondary Research Questions

b) Can the Design for Verification aid be successfully implemented to reduce production costs, reduce fixture redundancy, increase production rates and improve product conformance?

c) Can the Design for Verification aid be used to influence assembly processes, tooling design, tolerancing and metrology planning to reduce cost and time whilst improving product quality?

The fundamental role of the DfV guidelines within the DfX toolbox is to enable product conformance first time through ensuring verification capability based on early stage large volume measurement uncertainty analysis. This is coupled within a framework that aims to reduce manufacturing and metrology costs through integrated verification planning during early stage design. Excessive measurement and verification currently leads to elevated cost and production delays. It is proposed that through the implementation of DfV, early stage design engineers can be guided to the determination of assembly and tooling limitations in order to improve efficiency and increase rates of production through minimising reworking and delays due to metrology purposes.

1.6. Thesis Overview

In this section, the contents of this thesis are summarised by chapter.

Chapter 1: This chapter presents the need and motivation for the research from which aims and objectives are subsequently drawn. The research question is then presented to define the goal for the thesis. The main aims are declared for the creation of the DfV framework and the objectives are outlaid to define the proposed methods for which DfV is founded on.

Chapter 2: This chapter is a literature review with separate sections on four key areas relating to the proposed aims and objectives: DfX, measurement uncertainty, assembly and tooling for aerospace structures and tolerancing. Observations are discussed after each section to show the relation between the findings and the proposed research area. A summary is given at the end of Chapter 2 highlighting the proposed gaps in the knowledge in which this research seeks to fill.

Chapter 3: This chapter presents state of the art industrial examples that enforce and relate to the claims made within the observations sections within the literature review, Chapter 2. This is primarily to evidence the observations and provide the reader with a fuller understanding of the need and requirements for the proposed research.

Chapter 4: This chapter presents the response to the observed knowledge gap, discussed in Chapter 2 and Chapter 3. The overall Design for Verification framework is presented, showing the method for how it developed over time and resulted in the current format. The design guidelines, which aim to fill the observed knowledge gap, are presented and the steps are discussed in detail in the latter half of the chapter.

Chapter 5: In chapter 5, a case study is presented for the testing of the proposed Design for Verification framework. In order to prove the benefits of the guidelines, an existing assembly process for the Airbus Defence and Space Eurostar 3000 is used. The current processes are base-lined throughout Chapter 5 with respect to the structure of the DfV guidelines to lead on to a comparison through applying the guidelines in Chapter 6.

Chapter 6: In this chapter, the proposed DfV guidelines are applied to the existing Eurostar 3000 design and assembly process, previously detailed in Chapter 5. At the end of this chapter, the results from a design review, held with Airbus Defence and Space, are discussed, which form the foundation for the technology demonstration in Chapter 7.

Chapter 7: This chapter presents a technology demonstration that proves the design proposals derived from following the proposed DfV guidelines, presented in Chapter 6. A spacecraft like structure is designed, built and assessed. The tooling, assembly process and product design contain elements that are derived directly from the DfV framework. The hardware and process is described in detail throughout the chapter.

Chapter 8: In this chapter, the framework is discussed in relation to the defined aims and objectives and the research is assessed against the proposed research questions. Concluding discussions are drawn from the analysis and the research is critiqued.

Chapter 9: This is the final chapter of the thesis. It closes with a concluding summary which leads onto recommendations for further work relating to this research. A discussion is offered on how the Design for Verification framework could be improved through refinement and further case studies.

Chapter 2

Literature Review

It has been stated that 70%-80% of costs are defined at the design stage, whilst manufacturing can only influence 20%-30% [11]. There are in existence many guidelines for Design for Manufacture (DfM), Design for Assembly (DfA), and others within the DfX arena. The objective of this research is to build upon this knowledge and introduce a new framework, Design for Verification. Much work has been carried out on DfX, most notably by the software and literature developed by Prof. Geoffrey Boothroyd and Dr. Peter Dewhurst [12]. The software is targeted at the whole process and aimed at the professions from the shop floor to executive board as a tool for design optimisation towards stream-lined cost reduction in production [13].

Within aerospace, design includes multiple stakeholders that place numerous constraints on the deliverables. Stakeholders often hold agendas that are in direct conflict and as such have need for their interests to be viewed and negotiated through defined higher goals [14]. Multi-discipline design reviews promote the opportunity for stakeholders to have their agendas known if they are to be placed in a position where the design produced satisfies stakeholder constraints. Stakeholder interests are present from the highest abstract levels (cost, function) all the way through to lowest level operations and processes. With a customer brief established, manufacturing and process engineers require input at the earliest stages of design processes placing complex knowledge in the hands of the design team. The design team is required to understand the cost impact of their decisions, both up and downstream.

The following section looks at the work previously undertaken within the field of DfX. It then moves on to look at metrology with a focus on measurement uncertainty. The proposed DfV methodology relies upon knowledge and understanding of the uncertainty of metrology equipment so standard metrology instruments and techniques are reviewed within the following sections. Methods for assembly and tooling design within the aerospace industry are then considered in this chapter. Finally, tolerancing methods in relation to assembly and tooling design are reviewed because they are essential to the proposed methodology.

2.1. Design for X

DfX encompasses a vast range of both specific and generalised guidelines to aid designers in meeting predefined objectives in order to cost effectively achieve an optimal final product and work toward DFSS [1]. A key purpose of DFSS is to eliminate design vulnerabilities by ensuring that all the functional requirements of a product’s geometry can be maintained at plus or minus six times the standard deviation for each component so as to have confidence in the assembled end product with minimal costs incurred. The DfX guidelines that reside within the overall DFSS theory can be divided into subcategories for the different phases apparent within the product life cycle [15], summarised as:

1. Development phase
2. Production phase
3. Utilisation phase
4. Disposal phase

The success of the DfX concept was achieved through integrating small, focused engineering teams to achieve holistic DfX approaches ensuring that parts are designed with manufacturability and ease of assembly, with interchangeable parts. The concept of standardised and interchangeable components designed for large scale assembly was popularised by the requirement for the mass production of weapons by figures such as Lieutenant General Jean-Baptiste Vaquette de Gribeauval in 1765 and Honore Blanc in 1778 [16],[17]. In 1801, Eli Whitney successfully demonstrated this concept before the United States Congress which led to the standardisation of all United States equipment. This was a large leap towards modern manufacturing although Eli Whitney himself did not manage to achieve a manufacturing process capable of producing the interchangeable parts [18].

Arguably, the first successful implementation of part interchangeability within mass production was achieved by Marc Isambard Brunel (father to Isambard Kingdom Brunel) in 1803, shortly after Whitney presented to the U.S. Congress in 1801. This was during a time when the Napoleonic war was at a climax and the Royal Navy was rapidly expanding capability with a requirement for wooden pulley blocks. Brunel, working in collaboration with the esteemed Henry Maudslay, revolutionised the industry with a force of 45 purpose-built machines capable of carrying out 22 processes, able to produce three different sized pulley blocks. The processes involved marking the blocks and using features for alignment and creating datums, both showing and proving the integrated necessity for the concept of DfM [19], [20].

With the advances in manufacturing technologies such as milling machines and turret lathes, the concept of part inter-changeability, and the associated but still largely undefined DfM concept, spread throughout numerous manufacturing industries during the late 1800's including the locomotive, steam engine and sewing machine manufacturers. This paved the way for the introduction of the moving assembly line which was brought into fruition by the sponsorship of Henry Ford within the assembly process of the Ford T in 1913 - although general assembly lines can be dated back much further, even to the 11th century. Following the success of Ford's moving assembly line, the concept was widely adopted throughout many industries, satisfying the pressing requirement for assembly processes to keep up with the increasing capabilities of machine tools introduced through the industrial revolution and afterwards [21], [22].

It was not until more recently with the increase in computational power and software capability that assembly evaluation methods were created to rate assemblies and estimate time schedules and costs incurred such as the Design for Assembly method (DfA) by Geoff Boothroyd in 1977 or the Assembly Evaluation Method (AEM) by Hitachi in 1986, which were both crucial elements within the creation of the DfX philosophy [15].

The DfX concept, has been developed to aid designers through an entire product design process from conception to market release [23]. DfX has been recognised as one of the most beneficial design approaches in order to implement state of the art engineering solutions [1]. DfX has long been established and has steadily evolved to accommodate changing market requirements and technological advances. DfX has been described as the *"knowledge base to approximate the product design to the maximum of its desirable characteristics such as high quality, reliability, maintainability, safety, ease of use, environment constraints, reducing the lead times for sales, reducing manufacturing costs and product maintenance"* [15].

In Table 1, concepts are tabulated within their respective phases to provide an overview of where the author believes the knowledge gap exists. Within the development phase, DfX components such as DfTest, DfReliability and DfQuality are all encompassed and supported by verification with embedded design rules and assurance checks.

Table 1: DfX Classification and Definition

DFX CLASSIFICATION [1], [15], [23]	
DEVELOPMENT PHASE	Design for Safety
	Design for Clarity
	Design for Simplicity
	Design for Short Time to Market
	Design for Reliability
	Design for Test
	Design for Quality
	Design for Minimum Risk
PRODUCTION PHASE	Design to Cost
	Design to Standards
	Design for Assembly
	Design for Manufacturability
	Design for Logistics
	Design for Electronics Assemblies
	Design for Low-Quantity Production
UTILISATION PHASE	Design for User-friendliness
	Design for Ergonomics

	Design for Aesthetics
	Design for Serviceability
	Design for Maintainability
DISPOSAL PHASE	Design for Environment
	Design for Recycling
	Design for Active Disassembly
	Design for Remanufacturing

The aims of the research undertaken within this thesis, listed within Section 1.4, were to create methods for the following:

Objective 1: Metrology instrument specific constrained product design.
Objective 2: Metrology instrument specific constrained tooling design.
Objective 3: Measurement uncertainty informed tolerancing.
Objective 4: Measurement uncertainty constrained assembly tooling design.
Objective 5: Measurement uncertainty constrained process design.
Objective 6: Measurement uncertainty guided assembly sequence design.
Objective 7: Measurement uncertainty guided, verification based design.

These aims predominantly overlap with the DfX area, DfA, which arguably should reside in both the development and production phases [24]. Within the aerospace industry, these design phases are often addressed separately during early stage development, which results in products that are not optimised for full-scale production. This is partly due to the large scale of the projects undertaken but also due to the fact that a majority of engineers often only specialise within a single field or discipline [25]. Through the definitions in the literature, DfA can, in broad terms, be considered in two ways [26]:

1. Systematic methods for analysing assemblies [27].
2. General DfA heuristics [28].

The general DfA heuristics are most commonly communicated through two diagrams, with one representing poor DfA and the other representing best practice DfA. The heuristics have been criticised for their difficulty of use during design reviews [26] due to their graphical representation, which causes challenges in systematic application. The systematic methods for analysing assemblies, first conceived in the 1980s, led designers through a logical sequence to classify processes and score them accordingly. The three primary subdivisions of the systematic methods can be summarised as:

1. *Functional Analysis*: The process of determining the necessity of the component within the assembly, based upon an analysis of functional purpose, requirement for material difference, relative movement and the necessity for adjustment. This analysis leads the designer to consider if the part can be removed or combined with other parts to minimise the part count and therefore simplify the assembly.
2. *Handling or Feeding Analysis:* The process to ensure that the assembly components are fit for use with the assembly method. For human operations, the parts need to be simple enough to manipulate with good access, whereas parts for automation need to have well defined datum features for machine vision systems or mechanical part holding.
3. *Fixing Analysis:* the process of determining the optimum method for ensuring correct assembly through fastening methods whilst reducing the complexity of the fastening through any avoidable operations.

These methods have subsequently been designed into software analysis tools to simplify the tasks for designers and provide integrated knowledge based databases to build on previous models [29], [30].

Huang et al. [31] created a DfX shell to aid in the creation and application of DfX tools after recognising that designers found it difficult to choose an appropriate DfX tool for their given design task. It was proposed that a successful DfX tool would satisfy the following:

1) *“Most DFX tools usually do not generate design decisions directly. Instead, they evaluate and help to improve design decisions from specific points of view.*

2) *Successful DFX tools rationalize product and process designs by assessing not only individual design decisions but also their interactions.*
3) *Successful DFX tools provide pragmatic product and process models which are familiar to, or can easily become familiar to, their users.*
4) *Successful DFX tools define clearly their specific areas of concern, and thus provide the essential focus for the project team to make the best use of resources available to them.*
5) *Successful DFX tools focus on a few important aspects to evaluate the design decisions and their interactions. This allows the project team to view the subject problem from different perspectives without losing the necessary focus.*
6) *Successful DFX tools are equipped with logical worksheets, systematic procedures, and comprehensive data and knowledge bases, and are delivered as a complete package in the form of DFX handbooks, either paper based or computerised.*
7) *Successful DFX tools avoid unnecessary sophistication in modelling and measuring. Fabricated complexity is regarded as a hindrance to the main targets that DFX tools aim at achieving, i.e. communication and cooperation.*
8) *Successful DFX tools do not require collection of expensive data. Instead, these tools usually provide generic databases in the form of DFX manuals.*
9) *Successful DFX tools strike a balance between creativity and discipline, and also a balance between structure and freedom"* [31].

The nine proposed criteria for a successful DfX tool which could be presented in a common and standardised format were summarised by Huang et al. [31] through the acronym 'PARIX' (Product, Activity, Resource, Interaction, 'X' design area). It was observed that the increasing variety of DfX tools being introduced to the design sphere further rendered confusion as there existed no standardised DfX format. The introduction of PARIX attempted to overcome this, and as such, it is recommended that new DfX tools should follow the model [32].

2.1.1. DfX State of the Art

Due to the recognised significance of design optimisation for cost reduction and the pursuit of RFT manufacturing, vast resource is spent on conducting research within this area by both academia and industry. This section predominantly focuses on the state-of-the-art (SoA) within current research relating to the primary focus areas relevant to the proposed DfV framework.

Product design optimisation within a single DfX parameter can often, at first, cause detrimental consequences within other DfX parameters. For example, if one were to optimise a product purely for manufacture alone, the product would become significantly simplified to reduce cost and machining/production timescales. This, however, may reduce the product’s intended functionality by removing complexity required to perform specific operations during or post assembly. This dilemma inherently invokes a trade-off between the DfX optimisation parameters and has led to various attempts at a solution to resolve the conflict between optimising parameters against other parameters. This is a well-recognised challenge, often referred to as the principle of design parameter sensitivity, further discussed by Franciosa et al. [33]. The traditional approach to design optimisation is a sequential method, often referred to as a fixed point iteration method [34]. The challenge associated with this method is that it places heavy emphasis upon the skill set of individual designers. Franciosa et al. describe the lack of effective product optimisation due to limitations imposed on product design by a prevalent feed-forward approach, typically taken using the DfX approach where a feed-back loop would significantly improve optimisation efforts. Attempts to overcome this challenge have been initialised through the implementation of multidisciplinary design optimisation (MDO) methods which have aided the pursuit of closing the knowledge gap between distinct design sectors within large aerospace organisations. Applications of MDO have successfully enhanced the synergy between various design disciplines, pushing for a higher level of product optimisation [34][35]. Franciosa et al. [33] propose a novel methodology to aim at optimising heterogeneous design tasks with competing parameters such as in the example previously stated regarding the DfA and DfM trade-off.

2.1.2. Observations

Franciosa et al. [33] raise an important assertion which must be considered when developing criteria for a proposed enhancement to the DfX toolbox. Recent research has been conducted to modernise DfA and DfM techniques based upon the state of the art manufacturing capabilities within aerospace facilities. The quantification of process capability for individual processes plays a significant role within the optimisation of DfA and DfM. Process capability is calculated through the dimensional analysis of repeat parts from a given manufacturing or assembly process and provides a quantitative definition of the accuracy and precision of the particular process [1].

Whiteside et al. [36] produced a methodology which aims at incorporating process capability into early stage design using historic measurement data for a given process although it has been recognised that there is a clear knowledge gap within manufacturing and assembly process design when there is a lack of pre-existing process capability data. The observations stated by Whiteside et al. [36] that there is a knowledge gap within the design process is significant.

Measurement is the means by which an organisation can state and prove the conformance of an assembly or process and hence plays an integral part within manufacturing and assembly processes. Within the aerospace industry, when there is a lack of measurement data for a new product or process, the design team will often make assumptions on process capability to drive tolerance allocation. Process capability is a key parameter for defining realistic tolerances. This is especially challenging within the aerospace industry for examples such as spacecraft manufacture when products are often unique and generalised assumptions for measurement capability cannot be used to drive tolerance design. Existing rules within established DfA guidelines do not provide methods for designing capable assembly processes for the aerospace industry based on realistic assembly and measurement uncertainty.

The findings from the literature review on DfX have revealed that there are some key areas of importance that need to be considered during the development of the DfV guidelines. The first key factor is the recognition of the previous work undertaken to synthesise and channel information between design teams to holistically engineer an optimal product based upon the skills across multidisciplinary organisations. The DfV guidelines should complement this work so as to be readily implementable into current industrial processes. The second key factor for consideration is the previous work undertaken to incorporate process capability into DfX strategies. Process capability forms an integral part of product verification prediction for mass produced parts. Whilst this does not directly apply to low volume, high value manufacturing processes, concepts can be employed for the creation of the DfV philosophy to encourage predictive process capability modelling through alternative means such as instrument specific uncertainty modelling.

2.2. Measurement Uncertainty

This section gives an overview of measurement uncertainty. One of the key purposes of the DfV guidelines is to inform designers on the capability of measurement systems and uncertainty analysis so that product design can be improved upon from a metrology based perspective. Large volume is defined by the National Physical Laboratory (NPL) as a measurement that exceeds 1m, therefore the review of instruments in this section predominantly covers systems with the capability of measuring volumes larger than $1m^3$ [37].

2.2.1. Measurement and the Propagation of Uncertainty

Measurement uncertainty offers an estimated magnitude to unknown parameters for a given measurement. Dimensional measurements are never acquired with absolute confidence. Error and uncertainty in measurement data are present in many forms, illustrated in Figure 1, not all of which can be precisely quantified. Error and uncertainty sources are classified into systematic and random errors [38]. By nature, all errors are inherently systematic, however, errors that are caused by "*non-controlled random influence quantities*" are classified as random [39]. To quantify random error, the mean value between two observed random error distributions (Y) over time (X) is typically considered as the foundation for the uncertainty quantification as shown in Figure 2. The accumulation of the conceived systematic and random errors into an uncertainty budget allows a metrologist to estimate a given measurement uncertainty. Quantifying measurement uncertainty is necessary as it gives a validity to the obtained measurement. A measurement without an associated measurement uncertainty is somewhat meaningless as it does not provide enough information to determine the relationship between a measurement, the measurand and the engineering tolerance. The associated measurement uncertainty is essential in the determination of whether or not a part is within specification and the product conforms.

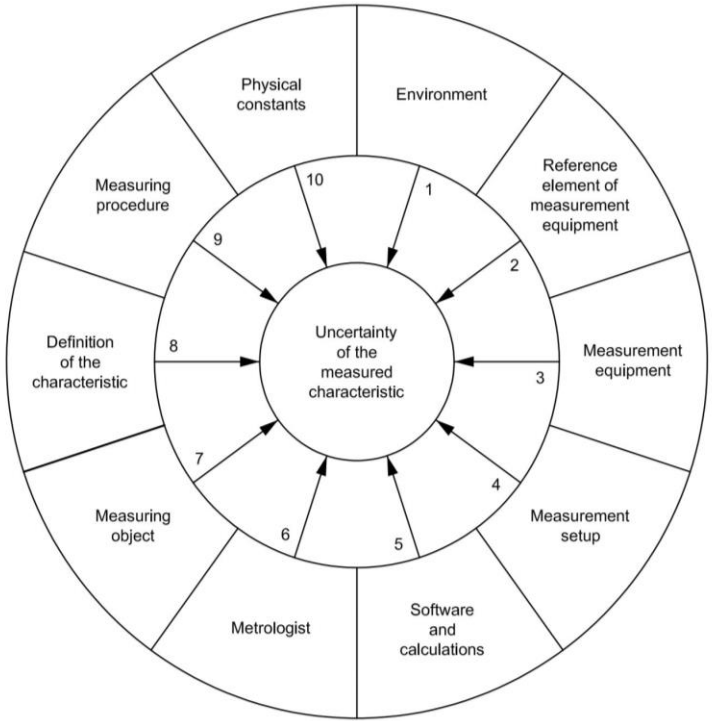


Figure 1: Sources of uncertainty. The outer ring gives examples of uncertainty sources and illustrates that they all feed into a combined uncertainty for the given measurand [38].

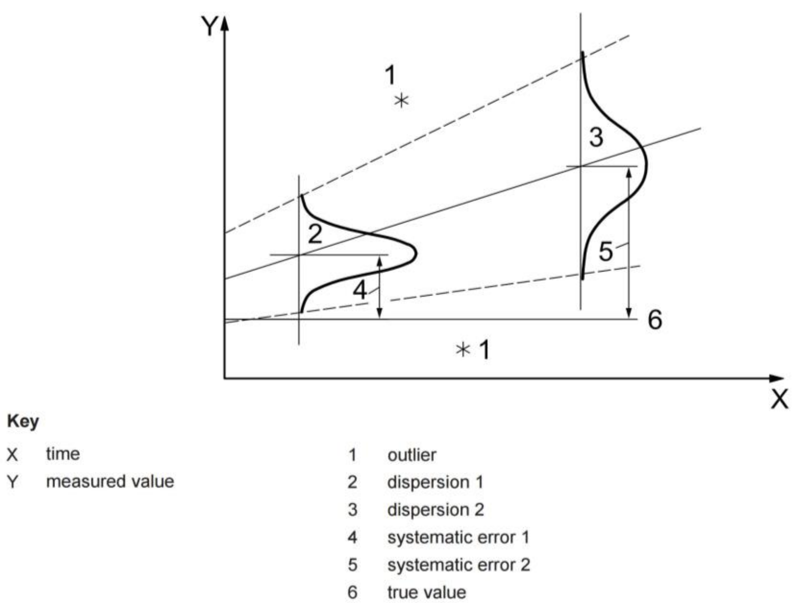


Figure 2: Random error quantification. Using the mean value within systematic errors to define the in-process measurement uncertainty [38].

There is a variety of methods for communicating and documenting the perceived disturbances found in measurement data for a given process. Two recognised approaches for quantifying uncertainty, predominantly used within academia, are found within the Guide to the Expression of Uncertainty in Measurement (GUM) [38] and that of the Monte Carlo approach. Industry tends to use an approach called Measurement Systems Analysis (MSA) [40]. GUM, Monte Carlo and MSA approaches are all valid however each approach tackles the challenge differently and can in turn render slightly different results. Muelaner et al. [41] described GUM as a bottom-up approach and MSA as a top-down approach and highlighted the advantages from both approaches. This led Muelaner et al. to develop a hybrid uncertainty estimation approach to combine the GUM and MSA methods in order to capture benefits from both approaches.

Measurement uncertainty is prevalent within all metrology systems. It is defined within GUM as the "*parameter, associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measurand*" [38]. Whilst uncertainty inherently tells us that there is something we do not know, it is possible to quantify the magnitude of what we do not know and apply a value to uncertainty, albeit an estimate. Measurement uncertainty can be estimated through the use of instrument specific uncertainty models. Models characterise and quantify instrument internal error parameters as well as the effects from external sources such as the environment including temperature variation, humidity, CO_2 levels and so on. A measurement, μ, is only complete when it is coupled with an associated uncertainty and given confidence interval as shown in Figure 3.

Measurements in large volume metrology are often a result of a combination of indirect measurements. GUM states that the relationship between the final result and the indirect measurements can be expressed in the form:

$$\boldsymbol{Y} = \boldsymbol{f}(\boldsymbol{X_1}, \boldsymbol{X_2}, \dots, \boldsymbol{X_N}) \tag{1}$$

where $\boldsymbol{X_i}$ are the discrete measurements and $\boldsymbol{Y}$ is the end result [38].

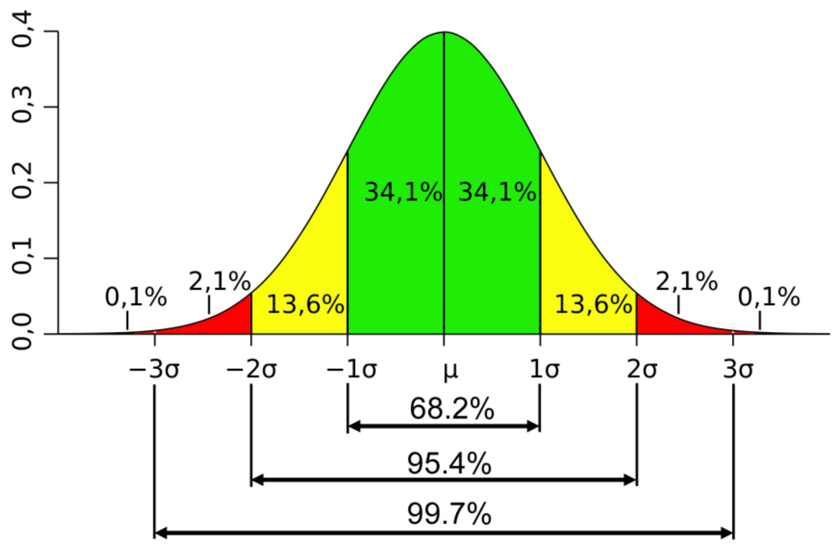


Figure 3: Normal distribution for a measurement [42] *with uncertainty and confidence intervals.*

This has been demonstrated in the example illustrated in Figure 4. The heights of the spacecraft cylinders *A*, *B* and *C* are measured directly, with corresponding standard uncertainties *u*(*A*), *u*(*B*) and *u*(*C*). Uncertainty can be defined through collating and combining all the major uncertainty sources as previously described and illustrated in Figure 1. The end result *Y* is the combined length of the spacecraft service module cylinders *A* + *B* + *C*. The uncertainty of *Y*, *u*(*Y*), can be estimated through propagating the estimated uncertainty of each cylinder using one of the methods previously referenced such as the GUM method:

$$u(Y) = \sqrt{u(A)^2 + u(B)^2 + u(C)^2} \tag{2}$$

After identifying the major sources of uncertainty as detailed within the ISO GUM standards, there are methods for managing measurement uncertainty within BS EN ISO 14253-2:2011 [43].

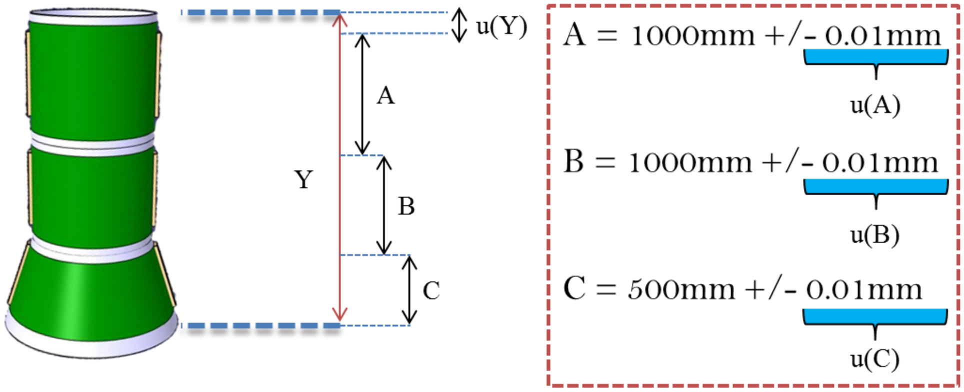


Figure 4: Satellite Service Module mock-up - Measurement uncertainty propagation.

$$u(Y) = \sqrt{u(0.01)^2 + u(0.01)^2 + u(0.01)^2} = 0.017mm \tag{3}$$

For cases where the standard uncertainty $u(x_i)$ is not given, it needs to be calculated for each component $x_1, x_2 \ldots x_N$.

For an assumed rectangular distribution, as seen in Figure 5, the standard uncertainty is calculated as (4).

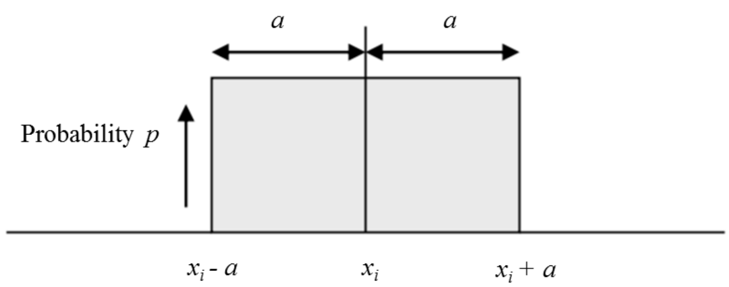


Figure 5: Rectangular distribution, image modified from [44].

$$u(x_i) = \frac{a_i}{\sqrt{3}} \tag{4}$$

For an assumed triangular distribution, as seen in Figure 6 the standard uncertainty is calculated as (5).

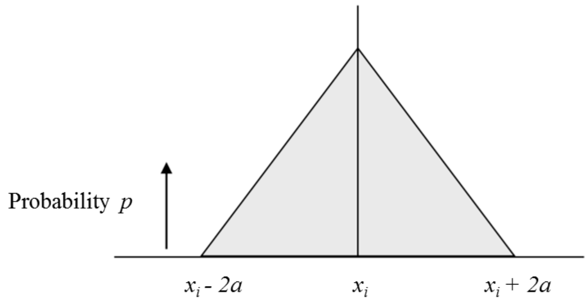


Figure 6: Triangular distribution, image modified from [44].

$$u(x_i) = \frac{a_i}{\sqrt{6}} \tag{5}$$

For an assumed U-shaped distribution, as seen in Figure 7, the standard uncertainty is calculated as (6).

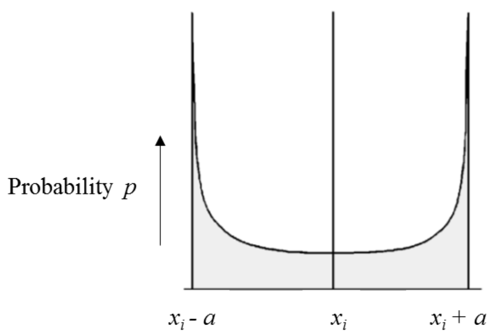


Figure 7: U-shaped distribution, image modified from [44].

$$u(x_i) = \frac{a_i}{\sqrt{2}} \tag{6}$$

For the example given in Figure 4, supposing the standard uncertainty values for Cylinder 1 and Cylinder 2 were given with a coverage factor of k = 2, and Cylinder 3 was given as a calibrated value, the uncertainty budget would therefore be represented as in Table 2.

Table 2: Uncertainty budget calculation [45].

Spacecraft Assembly Estimated Uncertainty				
Uncertainty Component (*Xi*)	**Value (µm)**	**Distribution**	**Divisor**	**Standard Uncertainty**
Cylinder 1	20.00	Normal	2.00	10.00 µm
Cylinder 2	20.00	Normal	2.00	10.00 µm
Cylinder 3	10.00	Rectangular	1.73	5.77 µm
			Standard Uncertainty	15.28 µm
			Expanded Uncertainty (k=2)	30.55 µm

For the uncertainty budget calculation example in Table 2, the estimated standard uncertainty is ± 0.015mm. A coverage factor k = 2 is applied to report the uncertainty within a confidence interval of 2σ.

2.2.1.1. Procedure for Uncertainty Management Part 1

This following sections details how measurement uncertainty should be managed following estimation. BS EN ISO 14253-2:2011 [43] details the use of the GUM approach to the expression of uncertainty within an iterative 'Procedure for Uncertainty Management' (PUMA). Due to the introduction of a GUM procedure that allows for iterations, the PUMA approach is a step towards the MCS approach in similarity. PUMA proposes two procedures for uncertainty estimation depending on the required task:

1. Uncertainty management for a given measurement process.
2. Uncertainty management for design and development of a measurement process/procedure.

The first approach of PUMA is aimed at directing methods for uncertainty estimation of pre-existing measurement tasks. The first iteration of PUMA is primarily to distinguish the dominant uncertainty contributors.

Through follow-on iterations, the PUMA approach guides metrologists to refine dominant uncertainty source estimations as seen in Figure 8 where U_{EN} is the estimated measurement uncertainty [39].

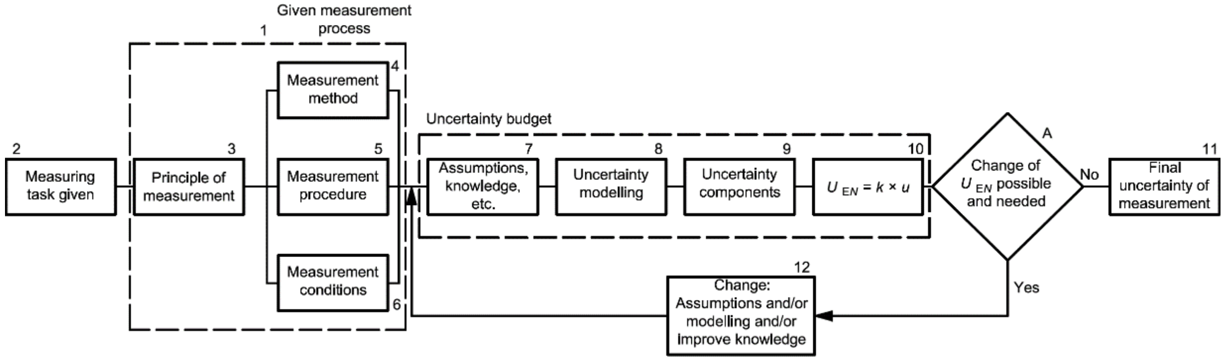


Figure 8: PUMA- Iterative GUM approach for existing measurement processes. Process steps 1 to 10 help the metrologist define if an alternative measurement system or method is required to complete the measurement with an acceptable degree of measurement uncertainty.

The second procedure detailed by PUMA is further explored in Section 2.2.2.5.1. Measurement process design is heavily dependent upon the engineering tolerances, measurement volume and product geometry as together, these parameters limit the measurement system that can be utilised. The follow on sections provide a brief description of the dominant metrology systems to detail their uses and limitations.

2.2.2. Common Metrology Instruments within the Aerospace Industry

The following sections give a brief introduction to the most commonly utilised measurement instruments within the aerospace industry for jig and fixture alignment. The instruments are introduced, most notably the laser tracker and photogrammetry systems, because the concepts underlying their usage forms the basis for discussion in later chapters and drives the principles behind proposals for jig designs as well as assembly sequencing in Chapter 6.

2.2.2.1. The Laser Tracker

The laser tracker was first invented by Dr. Kam Lau in 1986, who went on to create the now well established laser tracker marketing company API [46]. Laser trackers are now made globally by three main suppliers: Hexagon Metrology, API and FARO. An established technology with a Technology Readiness Level (TRL) of 9, the laser tracker is the dominant metrology system in the setting and verification of aerospace assembly tooling. Laser trackers operate with the use of a Spherically Mounted Retro-reflective (SMR) target. SMR targets, as seen in Figure 9, contain corner cubes (three mirrors aligned orthogonally to create an internal corner) to reflect the laser beam back along the same path it was projected from the laser tracker, termed as retro-reflective. SMR's have an acceptance angle (the angle at which a laser beam can enter the SMR and be reflected back) of around ± 30˚.

The fringe counting interferometer (IFM) is a distance measurement technology. Due to the speed and accuracy of which it can acquire measurements, it is commonly used for dynamic measurement of length within the laser tracker. The alternative is the absolute distance measurement (ADM) system, which is based on a time of flight principle and has historically taken significantly longer to stabilise during warm-up; this, however, has changed in recent years with ADMs becoming capable of accurate dynamic measurements within short warm-up periods [47]. Rotary encoders integrated into the laser tracker gimbal head (Figure 9) measure azimuth and zenith angles. When combined with the distance measurement from the laser, a target can be tracked through Cartesian space and measured dynamically. This is the principle method by which laser trackers operate and acquire measurements.

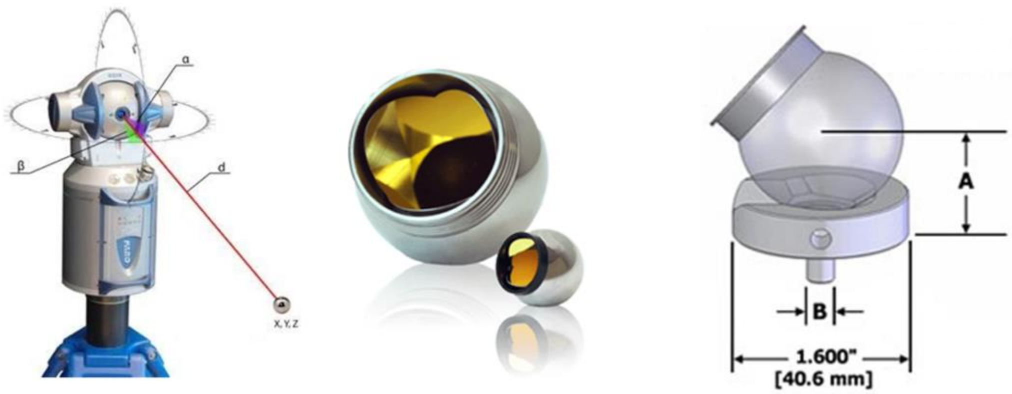


Figure 9: Left to right - Laser tracker, SMR, SMR seated on an SMR pin nest. Image adapted from [48]–[50].

Reference networks are typically used for laser tracker-to-CAD alignment. A reference network is a constellation of points that have a known location within 3D space in relation to a defined datum. Through measuring the points, an operator can perform a best-fit and align the laser tracker within 3D space to the measurand [51].

2.2.2.2. The Laser Radar

Laser radar is a similar but alternative system to the laser tracker, capable of measuring without the use of an SMR. Due to the laser radar being a relatively new technology, it has not had the same level of exposure in the aerospace industry as the laser tracker. The technology that drives the laser radar to operate without the use of an SMR causes it to be significantly more expensive in comparison. The laser radar utilises a frequency modulated infrared laser beam for distance measurement whereby determining the distance by calculating the time of flight. To accurately align the laser radar in relation to the measurand, it requires datum features to locate to such as spheres or planes, similar to that of the laser tracker. The ability of the laser radar to operate without the requirement for an SMR permits automated measurements of large surfaces. This feature can uniquely be used by the laser radar to perform self-alignment through best-fitting methods [52], which enables ‘hands-off’ large volume measurement. The process for which no human intervention is required.

2.2.2.3. Photogrammetry

Photogrammetry uses images captured from multiple camera positions and orientations to triangulate a point of interest within 3D Cartesian space using reflective markers as seen in Figure 10. The position of the target is calculated primarily from angular information, which is derived from the sensors and the calibrated principal distance between the sensor and the lens [53]. The principal distance is calibrated through the use and introduction of calibrated scale bars into the images near or next to the measurand.

There is a much higher availability of photogrammetry systems in comparison with the laser tracker. Low-cost systems are readily available off-the-shelf products, with ranging capabilities and accuracies. Photogrammetry is a highly accessible metrology instrument as it utilises technology common amongst the general public. Off-the-shelf cameras can be used to perform high-accuracy measurements with specialist software. Systems commonly used within the aerospace industry can achieve accuracies similar to that of the laser tracker with manufacturer's stated uncertainty values as seen in (7) [45].

$$0.01mm + 0.01mm/m \ \ (within\ a\ confidence\ interval\ of\ 2\sigma) \tag{7}$$

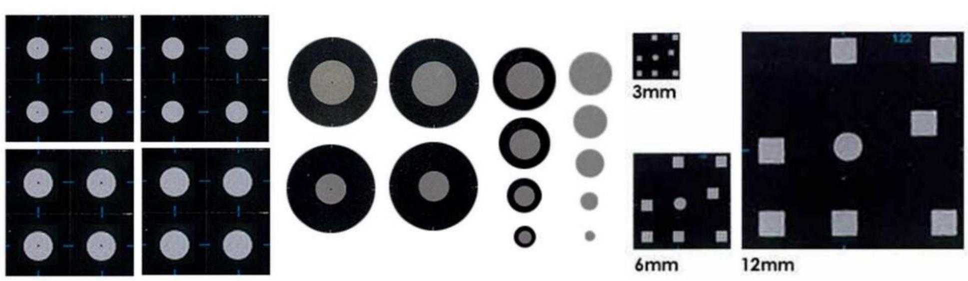


Figure 10: Photogrammetry targets. Image adapted from [54].

2.2.2.4. Articulated Measurement Arms

Portable measurement arms are used for high accuracy real-time geometric inspection as well as reverse-engineering. They have proven to be highly beneficial when inspecting parts that are inaccessible for metrology systems such as laser trackers or laser radars. The portable measurement arms use a series of angular encoders to determine the location of the probe in Cartesian coordinate form.

These portable coordinate measurement machines can be used alongside software such as Spatial Analyzer [55] to rapidly inspect parts to CAD to determine areas of variation between actual components/assembly and CAD within the same measurement frame as a laser tracker or photogrammetry system. With the option of laser scanner integration with many arms, it is also possible to rapidly scan surfaces for reverse engineering purposes.

Figure 11: Hexagon ROMER absolute measurement arms. Image adapted from [56].

2.2.2.5. Measurement Process Design

The role of metrology within high value, large volume manufacturing is fundamentally crucial to the successful implementation of assembly and integration processes. This section reviews the state of the art in metrology process planning for laser trackers to provide an overview of the challenges faced within the aerospace industry. The main challenges faced by metrologists are largely due to the limitations imposed on them by their measurement hardware or by the engineering design tolerances. The most commonly used metrology system within aerospace for tool setting, jig verification and product conformance evaluation is the laser tracker. The manufacturer specifications of available laser trackers are arguably quite similar, the stated uncertainty for Hexagon's flagship laser tracker, the Absolute Tracker 901 (AT901) (used by Airbus Defence and Space) is stated as 15µm + 6µm/m at a confidence level of 2σ [57].

Assuming the specifications of the AT901 laser tracker as a typical example of hardware capability for likewise systems, consider an assembly tolerance of ±50µm parallelism over 5 meters. A laser tracker measuring at a distance of 5m would measure with an uncertainty value of ±15µm + (6µm multiplied by 5) = 45µm at 2σ, illustrated in Figure 12, without considering the uncertainty of the tracker location relative to the part prior to jig measurement.

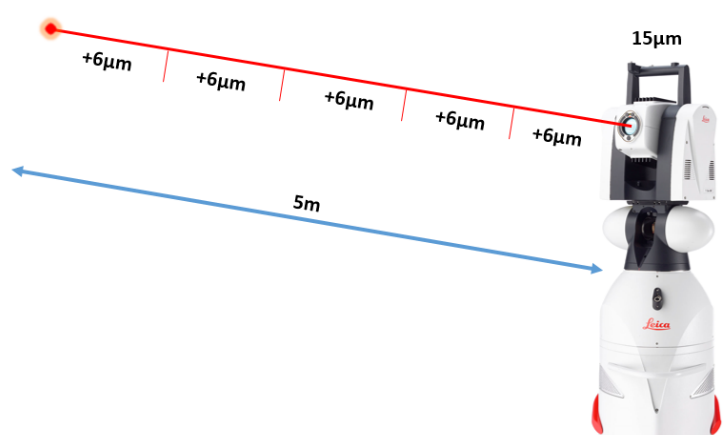


Figure 12: Laser tracker uncertainty increases over distance. The uncertainty of the laser tracker is 15µm + 6µm/m. Over 5 metres the measurement MPE is 45µm for the given example. Image adapted from [58].

This poses a significant challenge because it forces the laser tracker operator or assembly technician to achieve the parallelism requirement of ±50µm within a much tighter tolerance band of only ± 5µm to ensure that the assembly conforms with confidence to specification. Whilst this calculation gives a simplified view of the problem, it is still the most current method that shop floor technicians and designers employ to calculate uncertainty on a day to day basis. The effect of measurement uncertainty upon tolerance bands is illustrated in Figure 13. The illustration shows the effects of measurement uncertainty consuming the majority of the tolerance allocation which subsequently allows very little room for component deviation to ensure confidence in measurement. It is based upon an example using a confidence interval of 2σ, which is commonly accepted within aerospace communities. The pursuit of six sigma within the aerospace industry is largely unrealistic due to the physical scale of structural assemblies and the specification demands coupled with the currently available measurement hardware. Within metrology process design, there are many variables and unknowns which created challenges when attempting to fully model the environment and product to estimate true dimensions.

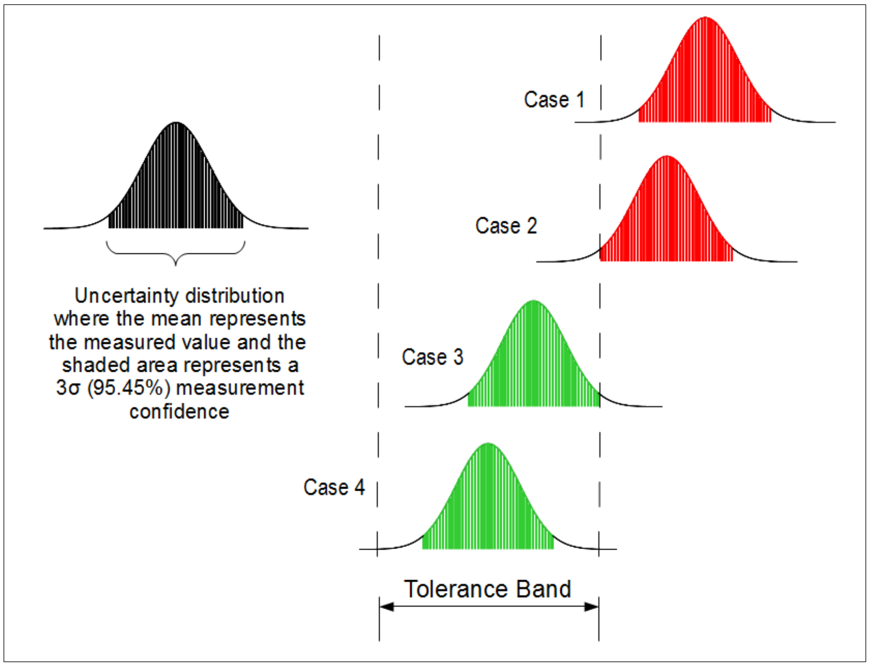


Figure 13: Effects of measurement uncertainty overlaying tolerance limits [59].

The actual in-process uncertainty of a measurement system can vary significantly depending on the environment and measurement strategy. In-process measurement uncertainty currently requires significant amounts of computational calculations and iterations with subsequent time delays, largely limited to highly skilled and experienced scientists. Commercially available software, such as the New River Kinematics Spatial Analyzer [55], have provided means of estimating measurement uncertainty using a simplified laser tracker model within a 3D measurement environment although use of this software is limited to highly skilled operators. The laser tracker model is based upon an angle–angle–distance uncertainty calculation as illustrated in Figure 14. The use of this simplified method can be misleading to the unknowing observer; the uncertainty estimation could be taken as an actual value, and so often within high value manufacturing it is. The effects of this has led to non-conforming products during assembly where multi-stage, international assembly operations are required. This is why it is essential that further complex modelling of metrology system process and uncertainty estimation is foundational during early design stages.

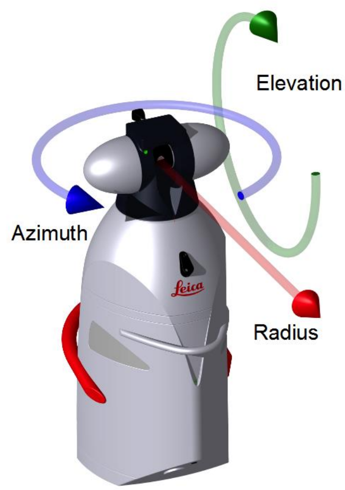


Figure 14: Laser tracker angle-angle-distance breakdown illustration [59].

The simplified method previously described introduces immediate errors due to the averaging, which is required to use this model. For this reason, although it is currently the best commercial solution, it should only be used as a rough guide and not a traceable and scientific means of measurement verification and validation.

Although the laser tracker does not currently have a commercially available software for calculating in-process measurement uncertainty, there have been attempts to quantify the error sources and develop laser tracker models. In 2010, Huo et al. proposed a Virtual Laser Tracker (VLT) framework model that claimed to account for all error sources affecting laser tracker coordinate measurements and proposed a model that could potentially behave “in an identical way to the real system” [60]. This model, however, failed to become a realisation due to the challenges associated with producing an accurate mathematical model for the laser tracker.

Advances in fundamental research for laser tracker measurement planning have progressed significantly since the development of an algorithm that was created and published by the UK’s National Physical Laboratory (NPL) for estimating laser tracker measurement error by using on a complex laser tracker simulator [61]. The research, published in 2011 then gave rise to further research programmes dedicated to improving laser tracker accuracy within industrial environments, with the NPL laser tracker simulation code at the heart of the research. Z. Wang at the University of Bath used the NPL laser tracker error estimation algorithm and bundled it into a ‘pattern searching’ algorithm for optimal laser tracker position determination. The code also supports the ability to import CAD models so that the optimisation algorithms can be calculated taking into account line of sight (LOS) challenges which are inherent with laser tracker. The purpose of the code is to provide laser tracker operators with a method to calculate the measurement uncertainty for a given process and also reduce the measurement uncertainty by optimising the position of the laser tracker [51]. The position of the laser tracker is highly important and has a severe impact upon the measured result if not carefully considered by an experienced operator.

Taking the simplified model as an example to illustrate this, consider the breakdown of the laser tracker. Two angular encoders are used for azimuth and elevation whilst an interferometer (IFM) or absolute distance measuring (ADM) laser beam provides the distance parameter to measure within full 3D coordinates. The angular encoders within the laser tracker are significantly less accurate than the distance measuring laser which follows with an uncertainty ‘cloud’ that is not 2 dimensional nor is it uniform or spherical as is usually assumed when single uncertainty figures are stated such as ±15µm + 6µm/m at 2σ within the previous example. The uncertainty cloud for the laser tracker is elliptical as illustrated in Figure 15.

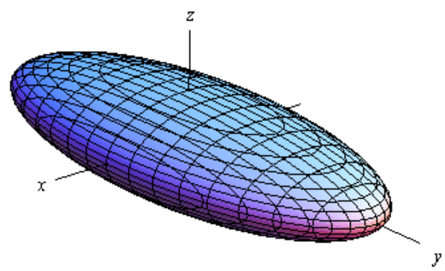


Figure 15: Elliptical measurement uncertainty from a laser tracker. Image taken from [62].

The understanding of this allows the measurement uncertainty to be significantly reduced by virtually overlaying measurements from different laser tracker positions as well as optimising the position of the laser tracker. This was tested and proven using a simple four point measurement, 3 station study. The theoretical study was conducted with the intent of highlighting the proof of concept and demonstrating the importance of laser tracker positioning and multi-station measurement. The results of the study, conducted using the NPL laser tracker model displayed in Figure 16, show a progressive reduction in uncertainty pre and post position optimisation. Uncertainty can be further reduced through adding additional laser tracker stations. Considering the timescales involved in adding additional stations, it becomes a trade-off analysis depending upon the accuracy required.

This study proved the significance and importance of the work conducted by NPL on the advanced laser tracker model and the subsequent pattern searching algorithm, which used the model to optimise the position of a laser tracker within a 3D measurement environment [51], [61]. Whilst the Matlab script, based upon the NPL laser tracker code [61], produced by Wang [51] has proven the potential to be very useful within the manufacturing sphere, it has yet to be employed within the early structure design phase which is where the author believes it could be most valuable and serve as an important factor within the DfV philosophy for tolerance allocation and process planning which would have a significant impact upon structural design. Maropoulos et al. [63] proposed a novel approach to large volume high value manufacturing under the title of Metrology Assisted Assembly (MAA).

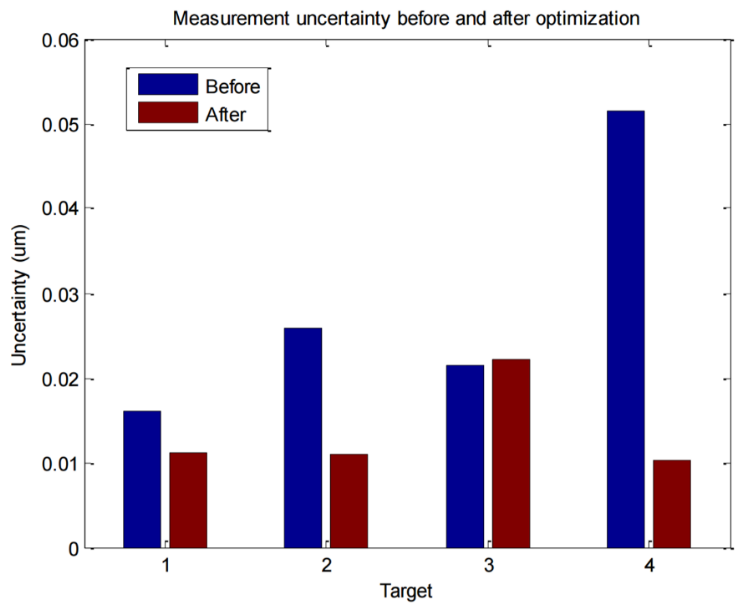


Figure 16: Laser tracker measurement uncertainty reduction using positional optimisation [51].

The MAA philosophy proposed a novel method using the SoA in large volume metrology systems to provide real time metrological feedback and verification for jig setting and assembly alignment. The paper outlined the latest developments in aircraft wing assembly with respect to MAA and developed a process to promote RFT manufacturing during the assembly stages. The build paradigm selection process outlined a novel approach to assembly tolerance analysis, but failed to consider a metrology system uncertainty feedback loop into the design phase, however, previous research has been conducted which highlights a need to consider measurement uncertainty in early stage design to enrich tolerance allocations [10]. This was also true for the following research undertaken by Muelaner et al. to further the MAA model into the Integrated Dimensional Variation Management (IDVM) build paradigm [64].

Maropoulos et al. [10] recognised the need to consider laser tracker uncertainty within high value aerospace structures design, building upon works such as ‘Advanced Tolerancing Techniques’ by Zhang [65] who presented the general concept. This work, however, neglected recognised and established methods for uncertainty quantification and estimation such as the standards UKAS M3003 and the Guide to Measurement Uncertainty (GUM) [25],[26],[44]. The purpose of incorporating traceable measurement planning and uncertainty estimation within the early aerospace structure design stages would provide a realistic set of limits upon manufacturing and assembly tolerances. The importance of an aerospace supplier possessing the capability to verify product conformance to specification is of paramount importance. If the supplier is unable to prove that manufactured products meet design specifications, then the customer would have means to reject the product which could potentially be a significant financial loss [59]. The current lack of effective metrology planning and measurement uncertainty estimation using recognised international standards and methods within the early design phases for aerospace structures represents a risk to product quality when tolerancing engineers have little experience or cross communication within multidisciplinary teams as experienced during industrial collaborations.

2.2.2.5.1. Procedure for Uncertainty Management Part 2

The first part of PUMA, found in BS EN ISO 14253-2:2011, deals with estimating measurement uncertainty for a pre-existing measurement, further detailed in Section 2.2.1.1. The second part of PUMA provides a process for estimating measurement uncertainty prior to measurement when there is a given target uncertainty U_T as seen in Figure 17. This is described here as it provides a foundation for the concepts behind linking measurement uncertainty estimation with early stage design.

The purpose of the PUMA process is to develop a capable measurement process with an adequate measurement uncertainty based upon design requirements. The aerospace industry commonly accepts measurements stated within a confidence interval of $2\sigma = 95.45\%$

although this is often at the discretion of the manufacturing department. Adequate measurement procedures result in estimated measurement uncertainty that are less than or equal to the required uncertainty [39].

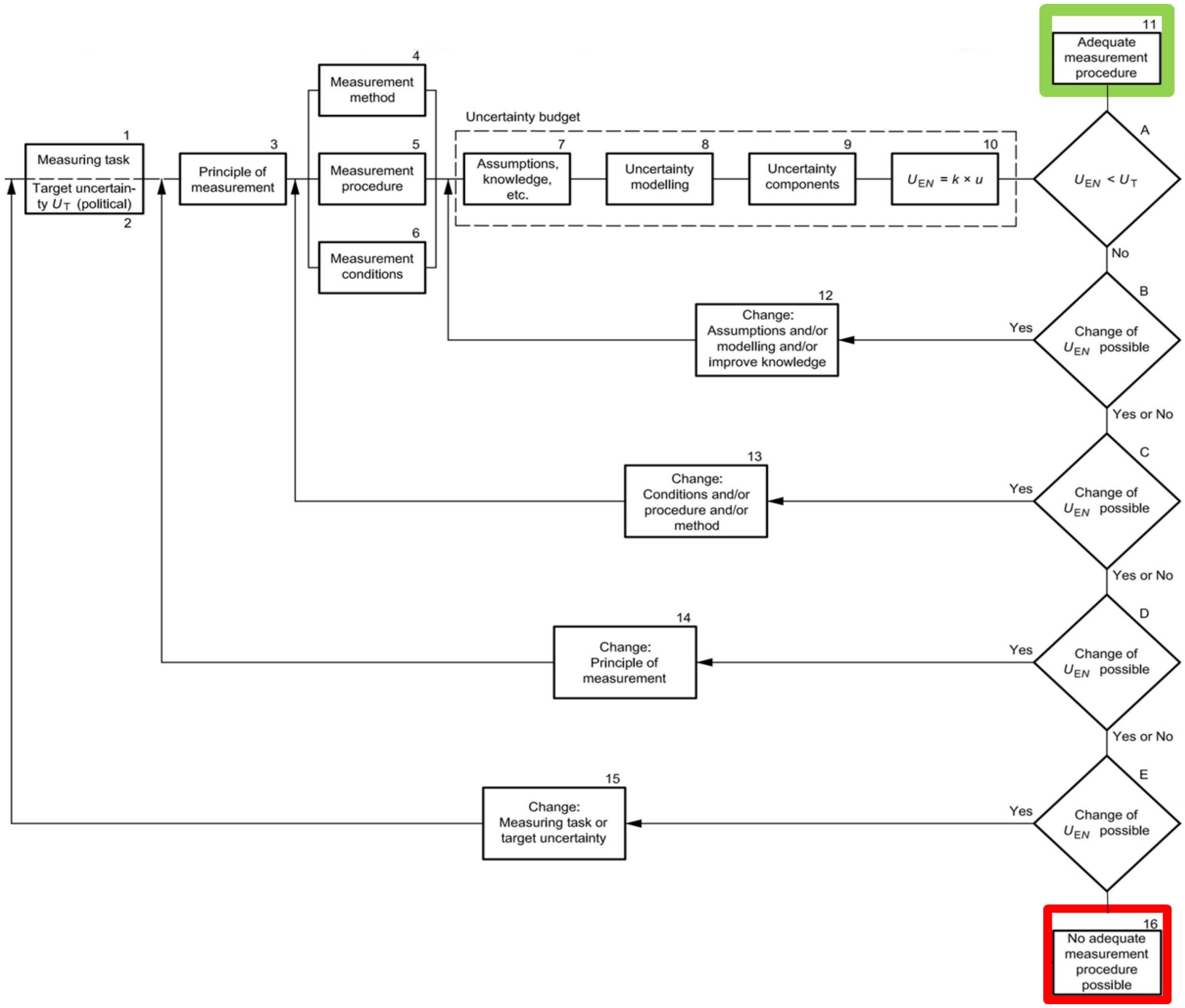


Figure 17: Procedure for Uncertainty Management Part 2 – Estimating measurement uncertainty prior to measurement procedure to define measurement system suitability [39].

The PUMA process is similar to MSA in that it provides methods to determine in-process uncertainty for a given measurement through practical experimentation [40]. A limiting factor within the PUMA process is that it requires a product, in order to undertake measurements of, to calculate the measurement uncertainty. This is significant because it requires a product that is significantly mature in design, at least at the prototype stage.

2.2.3. Observations

The literature review has revealed the necessity for measurement planning during early stage structure design coupled with traceable uncertainty quantification and analysis. The measurement process drives the accuracy of the final assembly as well as the verification process confidence. In order to ensure that aerospace products conform to specification, the specification must be based upon measurement process adequacy. Tools such as the laser tracker position optimisation code,[51] based upon NPL's traceable laser tracker simulator [61] could provide beneficial early stage design limits if implemented within the DfV philosophy to establish rules for assigning tolerance limits and desired confidence levels.

The measurement process planning aspect of the DfV framework should be used to guide structural assembly methods based upon instrument specific requirements. The methodology presented by PUMA part 2 could be advanced if it were to be considered during early stage design and combined with assembly sequence analysis, stress testing and uncertainty propagation estimation. For example, if the early stage measurement process design revealed that the only suitable metrology instrument for post-assembly structural verification was the laser tracker, then assembly features and datums as well as product KCs would be defined based upon the measurement characteristics of the laser tracker to ensure confidence in measurement. The measurement simulation to define the in-process uncertainty could then be used to reduce uncertainty whereby optimising assembly sequences and tooling design. Subsequent assembly stages could then be simultaneously modelled and optimised for the use with the chosen metrology system for tool setting and verification. The DfV guidelines could be supported by an environmental model or at least a working knowledge of the assembly area in order to optimise precise assembly planning routines. The environmental model could be used to guide both metrology planning and tooling design. More specifically, tooling design could be enriched through an environmental model by minimising areas of high uncertainty due to thermal gradients and unpredictable air flow.

2.3. Assembly and Tooling for Aerospace Structures

In the previous sections, metrology principles and common instruments used for tool setting and product verification in the aerospace industry were introduced. The constraints placed by measurement uncertainty was also explored in relation to tool setting and verification (see Section 0). This leads to the following section which provides an overview and critique of aerospace structure assembly tooling. A review of assembly sequence process design and tooling for aerospace structures is presented to inform discussions on the proposals within the DfV framework (Section 0).

2.3.1. Conventional Assembly Tooling within Aerospace Industries

Assembly systems have been classified into three categories [27]:

Manual:	Manual labour of skilled and semi-skilled technicians.
Flexible:	Automated assembly systems capable of reconfiguration with minimal cost.
Dedicated:	Monument system bespoke for single operation use.

Aerospace tooling predominantly falls within the *dedicated* category. Current fixture design for high value low volume aerospace products is a very lengthy process and is characterised and dominated by the use of large monolithic steel jigs as seen in Figure 18 for Type 2 assemblies (see Section 2.3.3). Whist this presents obvious benefits such as high stability and rigidity over long time periods, capable of taking accidental knocks during manufacturing, it also carries many disadvantages. The disadvantages associated with large monolithic steel assembly frames are largely surrounding their inability to adapt to changing product design as with *flexible* assembly systems. They are highly inflexible and are subsequently very costly to adapt and rework for alternative product design variation.

Tooling design teams have historically benefited from much closer relationships with metrology teams within aerospace communities. Large volume fixtures are often more equipped and metrology friendly when compared with the products being assembled. This has led to challenges within direct verification of the product. The steel jig pictured in Figure 18, is a typical example of a SoA jig that is found within the spacecraft manufacturing community. The purpose of the jig is to hold the critical interfaces of the spacecraft around its extremities, to control the critical mating surfaces for follow on assembly stages, whilst the inner structures are bonded or bolted together using open tolerance friction joints. Within the spacecraft community, the production of assembly jigs has been largely unchanged since the first commercial spacecraft was constructed.

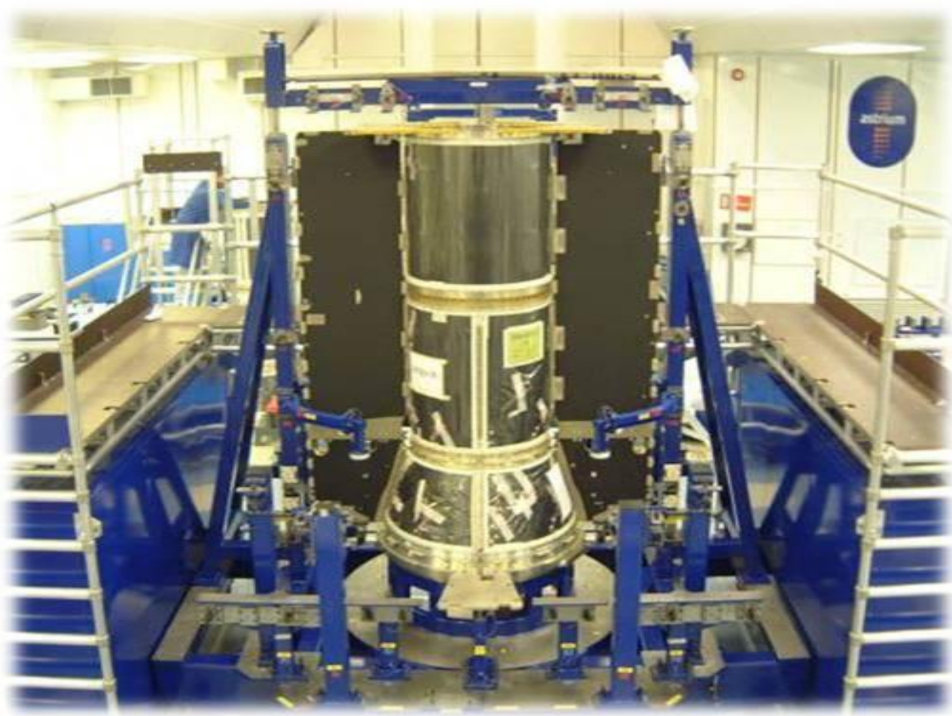


Figure 18: Service module Level 2 assembly jig, 2013 courtesy of Airbus Defence and Space, Stevenage.

The historic relationship that tooling teams have had with the metrology community has led to directly measurable, embedded key characteristics (KCs) to improve product conformance. KCs are geometric features that are precisely constrained to maintain customer requirements and product performance [66]. The previously mentioned relationship between tooling design and metrology has evidenced a necessity for multi-disciplinary design working within early stage product development as the learnings have yet to translate into product KCs [67].

2.3.2. Modern Aerospace Tooling Design

The design of fixtures and jigs within the low volume high value manufacturing sector has been slow within the uptake of innovative solutions, largely due to the risk associated with manufacturing high value products and the associated costs involved. The synergy between tooling designers and metrology experts is beginning to pick up pace within the past few years although there is still no formal solution to the synergy as the methods are still being developed to enable this [59]. Flynn et al. [68] published a paper upon the need to integrate automated metrology technologies into the assembly of wing structures. They highlighted the costly time delays in the current process where recertification and verification of a wing assembly jig can cause a jig to be unusable for up to a week at a time per jig [68]. The solution proposed within this paper was to develop a software solution to deskill the metrology operation and decrease the amount of time taken to perform the tasks. The paper concludes that it was a challenging task but there is a strong possibility to improve the process through the deskilling of the methods and automating of specific measurement tasks. Whilst this paper provided a valid potential solution to reduce recertification timescales for assembly jigs, it fails to effectively obtain a working solution and also to design a process for verification using the state of the art in metrology expertise. DfV would need to consider the necessary overlap between tooling and metrology to optimise tooling design for metrological verification and the integration of metrology directly into tooling structures.

The integration of metrology systems into tooling structures had been explored previously by Muelaner et al. [59]. The method proposed a novel metrology based structure that encased a network of embedded interferometers to measure tooling pickups in real-time within an existing wing assembly jig. The purpose of embedding the interferometer network directly within the steel jig was to shield the laser beams from the environment to reduce the uncertainty accrued from the measurement so that a highly accurate measurement network could be formulated. The paper presented the embedded interferometer network as "*the most* *advanced solution*", however, when the paper was subject to peer review, members from NPL highlighted the uncertainty propagation which would accumulate through the extended network, rendering the network impractical for the aerospace community [59]. The conjecture of embedding metrology systems directly within tooling structures is recognised as a proposal which has potential viability for aerospace tooling and should be highlighted within the DfV process during application.

It is recognised that in order to improve tooling efficiency and adaptability for growing market demands, tooling within aerospace would need to become increasingly flexible and intelligent. Tooling specialists within aerospace, have invested in developing novel reconfigurable tooling instruments for high reconfigurability. This has led to the realisation of the importance of metrology system integration and research is continuing within the realms of developing a solution to tooling-metrology hybrid. In 2009, Millar et al. worked with an academic organisation to initiate the use of an immature reconfigurable tooling proposal [69]. The project for Airbus was supported by DELFOi, a spin-out company from Linköping University that helped develop the tooling strategy [69]. The paper showed the advantages of using the reconfigurable tooling but highlighted the disadvantages inherent within the system such as the difficulty in reconfiguring the tooling and the advanced expertise required in jig building and laser tracker operation in order to achieve a suitable and comparable result to the current methods[69]. The DfV framework will need to consider the advantages of reconfigurable tooling with the capability of cost effective reconfiguration and alteration. The challenge of integrating reconfigurable tooling into the aerospace sector would be to design a system, which could accommodate the tight tolerance demands over the large volumes.

An alternative to replacing the large monolithic steel jig structures with like for like reconfigurable tooling components would be to design the product during the early stage concepts, to enable jigless assembly. This is something that has been explored in previous years, although has been, to date, unsuccessful. The process of moving towards a jigless assembly has many complications to consider with large volume assemblies. The gravitational and thermal deflections incurred from the part during assembly over large volumes can be in the region of millimetres. Without the ability to control critical interfaces with external hard tooling presents many challenges. Naing et al. constructed a framework proposal for achieving jigless assembly of an A320 [70]. The framework included an assembly analysis of error propagation through a statistical approach, identical to tolerancing error propagation models using the root sum square (RSS) methods. This approach failed to incorporate the necessary instrument uncertainty at each stage in order to build an accurate model and may account for one of the reasons of its failure to be successfully implemented for complex assemblies with many components. The model did, however, include a cost estimation based upon process characteristics which should play an essential role during early stage product design for valid cost estimation.

The philosophy of measurement-assisted assembly has progressed for jigless assemblies where significantly fewer parts are mating during the process. Software for calculating optimal best fit parameters for individual components has been developed to assist large volume assembly operations such as wing to fuselage and fuselage to fuselage mating processes [71]. This has been largely progressed from research into industrial solutions and is at a relatively mature stage, being employed globally for the assembly of military aircraft. The enabling technology was provided by various tooling suppliers, but DURR appear to possess the most advanced solution with their Ecopositioner, illustrated in Figure 19 [72].

The Ecopositioner, whilst appropriate for increasing ramp up rates for military aircraft, the absolute accuracy is stated at ±0.1mm which would not suffice for the low volume high value industry where tolerances of ±0.05mm are more common over large volumes.

Tooling strategies often enable the structural verification of products pre and post intermediate operations such as non-destructive testing (NDT) by way of acting as a go/no-go gauge. Large fixture interfaces are set to specified positions with the aid of laser trackers in real-time which are then secured in position, often bonded into place for added rigidity [59]. This means that the product structure is only ever as good as the jig, placing a heavy emphasis upon the tool setters to perform at a highly complex level.

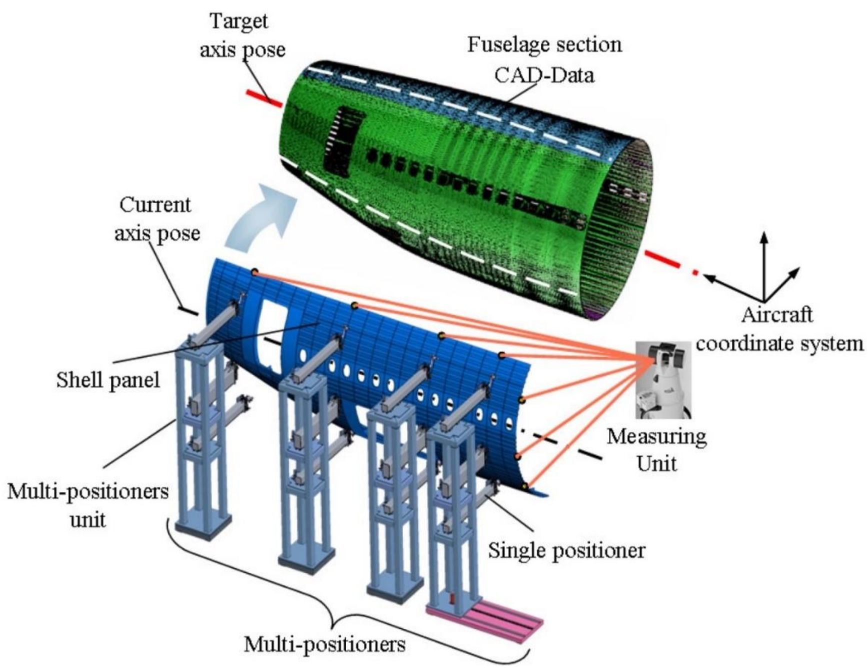


Figure 19: DURR Ecopositioner. Image taken from [73].

The interfaces positioned by the tool setters are commonly the critical interfaces, which hold the key characteristics (KCs) for further assembly operations. The most direct way to verify the product structure would be to measure the KCs directly instead of relying upon the jig as an indirect verification method. Vakil [67] published a methodology in attempt to meet this challenge when faced with measuring the KCs using multi-instrument networks in order to obtain a common datum [67]. The proposal presented methods commonly used within the metrology community for locating a variety of systems including photogrammetric, articulated arms, laser scanner and trackers into a global reference system. The paper highlights the best practise for achieving this in attempt to make designers aware of the requirements for metrology systems within the manufacturing and tooling sectors. The paper is a valuable resource for use during early stage design although it failed to communicate the crucial importance of measurement uncertainty and network optimisation [67] during early stage design to drive tolerance limits on KCs. DfV will need to raise awareness of multi-instrument networking but further this and highlight the need for optimisation to achieve optimal confidence in KC definition.

2.3.3. Assembly Sequence Process Design

Within the previous sections, the limitations of setting large aerospace assembly tools with common metrology instruments was made clear. The impact of measurement uncertainty when acquiring measurements over large distances was described and the current status of aerospace tooling was explored. This section looks into assembly sequencing concepts and limitations and relates the findings back to the impact upon measurement uncertainty and how they affect product conformance within the aerospace industry.

2.3.3.1. Datum Flow Chain Analysis

Mantripragada et al. [66] describe a concept for assembly sequence design called ‘Datum Flow Chain’. Within the concept, two types of assembly are assessed:

> *Type 1*: an assembly that is defined by the accuracy of the parts being assembled. Each of the parts within the assembly contribute to the assembly variation through the errors introduced from prior fabrication stages.
>
> *Type 2*: an assembly that is defined by the accuracy of the fixture used to assemble the piece parts. The assembly has only *contacts* between the components as opposed to *mates*. The *mates* reside on the external interfaces with the assembly fixtures and control the KCs.

Type 2 assemblies are most common with the aerospace industry and therefore the focus within this research. Within Type 2 assemblies, overall accuracies are driven by the capability of the process to transfer datums from the assembly tooling to the product with minimal geometric disturbances. These datums are defined by KCs within the tooling and product. This is achieved through the selection and embedding of features in optimal locations. This invokes a trade-off between tooling and product design such that the tooling can be created to hold the assembly components true to the intended form whilst maintaining the ability to be calibrated and adjusted when required [59]. It has been recognised that product verification would be significantly improved post-assembly if the datum features transferred from the tool to the product were directly measurable [67]. This would lead to reduced time in measurement and promote design founded on instrument uncertainty estimation (see Objective 1 Section 1.4). One of the greatest sources of uncertainty in large volume metrology instruments is the environment. The following section explores the implications the environmental effects upon aerospace assemblies.

2.3.3.2. Environmental Impacts on Aerospace Structures Assembly

Assembly sequencing is heavily dependent upon product structure design. DfA addresses the importance of early stage consideration and optimisation for ease of assembly and minimisation of parts for complex products [26], but within aerospace assembly, one of the major limiting factors for successful assembly is the impact of the environment. Large volume assembly processes for aerospace or marine structures often occur in large, environmentally uncontrolled open spaces. It has been observed that there are often shutter doors directly to the outside world within assembly rooms to enable access for the assemblies to enter or leave the building. The assembly areas typically have rows of fan heaters located around the building to keep the area at a reasonable temperature for the workers to conduct manual labour.

One such example is of the Roll- Royce marine plant in Ulsteinvik, Norway, where it manufactures and assembles large volume marine products. The facility is located on a dock so that repairs and overhauls can occur without additional expenses from transporting marine structures across land. The temperature differentials between the outside and the inside of the facility can be considerably substantial with average outdoor temperatures during the winter months at around 3℃. It was observed that the use of the shutter doors and automated heating systems lead to the turning on and off of fan heaters, which created hot spots throughout the factory environment with additional unwanted air flow.

Studies within a temperature controlled assembly environment at the Airbus Defence and Space (Stevenage) site revealed that across a single jig, on a relatively stable day without significantly altering the environment through the use of heater fans or opening shutter doors, there is still a vertical temperature gradient across a single 5m jig of up to 3℃.

As previously discussed (see Section 2.2.2.1), the laser tracker is the gold standard for dimensional verification within large volume applications where high accuracy is required. Thermal, carbon dioxide, pressure and gravitational variations can have significant impacts upon laser tracker measurements [74]. According to the ASME B89.4.19, over a distance of 3m and a temperature gradient of 1℃/m, the uncertainty of the laser tracker is increased by 13.3μm within a 3σ confidence level ~=99.7% certainty [74]. Under this basis, design should consider environmental stability as a factor during time scheduling for assembly procedures to increase certainty in measurements.

2.3.3.3. Recent Developments in Assembly Sequencing

The first stage of assembly process planning is to optimise the scheduling for all prior manufacturing processes to ensure that all required parts and components for the end product arrive at a final assembly in synchrony. The second stage of assembly process planning is to create a streamlined assembly sequence (see Section 2.1). Metrology within the process is viewed as a non-value added task and there is a drive within aerospace to minimise metrology processes because of this [75].

Methods for automating assembly planning based upon ease of assembly with respect to product configuration have been proposed. CAD based assembly mapping products are becoming more advanced and capable of optimising assemblies [76]. Nibandhe [77] proposed a “New Approach to Automotive Vehicle Assembly Process”, which defined a novel framework for assembly planning in order to verify products within the early stages of manufacturing for New Product Development (NPD). Early stage optimisation for assembly planning and sub-assembly verification would benefit from further optimisation through design whereby integrating metrology system limitation characteristics.

Factory layout considerations have been discussed since the industrial revolution. Moehle [78] further raised the importance of factory layout within aerospace assembly lines in order to increase flexibility for design variation within the aerospace industry on the basis that rising demands for state of the art technologies on assembly lines will lead to an increased turnaround of tooling hardware and processes to satisfy customer requirements [78]. The integration of a specialised design guideline within the early stage development of an Integrated Assembly Line (IAL) could significantly enhance flexibility potential for tooling and processes by optimising the factory layout to promote adaptability, enabled through enhanced metrological verification.

Specialised design guidelines within high value, low volume assembly process planning could raise awareness of metrology and verification limitations within the jig setting, jig verification and product verification processes so that assembly process and factory layouts could be optimised for enhanced verification based upon factory specific environmental conditions. Where metrology and assembly processes are still distinguishably separate within low volume high value manufacturing, the assembly process planning phase does not consider the role of metrology within processes based upon metrology system limitations.

Environmental limitations upon laser tracker based measurements constrain the accuracy that can be achieved. The most prominent cause of measurement error within industrial environments is thermal gradient variation, however, other significant factors exist such as gravitational effects i.e. moving bodies of water (tidal, rivers etc.), or carbon dioxide pockets within the measurement volume. Through the better understanding of metrology instrument capability, enhanced assembly processes and philosophies can be designed.

An assembly philosophy can have a significant impact upon the end product functionality and it can also effect product conformance to specification. For example, every E3000 spacecraft manufactured is bespoke, even amongst the same models. This is purely because of the challenge associated with controlling interfaces over large volumes to the required tolerances ($< 50\mu m$) within the associated assembly philosophy which the product design is based upon.

The successful implementation of a part-to-part interchangeability assembly philosophy for the Airbus Defence and Space Eurostar 3000 would significantly improve market holding by decreasing production timescales and subsequent labour costs. In order to realise this philosophy Airbus Defence and Space would need to invest significant time and research into novel assembly processes and technologies as well as an optimised product design for the alternative assembly philosophy.

The impacts of the environment during assembly operations upon optical based measurement systems is significant enough for metrology processes to be considered during the time scheduling of large volume assemblies with respect to time of day, location of assembly and parallel processes which may impact the environment such as planned deliveries of components, which cause shutter doors to open etc. As well as the effects of the environment upon optical metrology systems, assembly jigs also suffer from thermal expansion and contraction. This means that time scheduling will need to consider stable times during the assembly lifecycle for conducting critical assembly operations. One notable example of this was discovered during assembly of the RAF's Typhoon. The effect of the tide of a nearby river due to the gravitational pull of the moon created disturbances within the assembly environment causing the assemblies to be out of tolerance. This could have been overcome by adjusting the tolerances to account for this which would have required significant redesign of the aircraft, or by altering the assembly tooling and sequence to manage the environmental effects. Within this particular example, BAE invested in sophisticated electro-mechanical systems to adjust for movement in the facility foundations during times of high tide [79].

2.3.4. Observations

The importance of highlighting metrology requirements for end product verification in early stage design phases for tooling design within a multi-disciplinary team has been recognised as of significant importance for a successful DfV proposal. KCs and critical interfaces for a Type 2 assembly of a product structure must translate to tooling datum points, which are directly measurable by large volume metrology systems, for both tool and product. The KCs that hold the critical mating interfaces can then be used for optimal assembly procedures and, if necessary, predictive fettling and shimming operations prior to final assembly. An early stage trade-off analysis of the KCs could also incorporate cost modelling with respect to tooling design and the effects of increasing the number of KC interfaces.

The proposal for integrating metrology systems directly within tooling structures poses significant potential for progressing to smart tooling capable of monitoring critical interfaces against predefined tolerance bands in real-time. Early stage optimisation of KCs for assembly, based upon tooling and metrology limitations would enable the option for integrating metrology for advanced in-process verification. Coupled with an autonomous tooling system, if realised, the solution could provide a pathway for automated verification and further innovation.

Tooling for final assembly lines is designed to have a degree of flexibility, or adjustment, so that it can be set to as accurately as it can be measured and manipulated by an operator as typically seen within Type 2 assemblies. This leads to the conclusion that early stage metrology process planning and subsequent measurement uncertainty estimation should be the foundation for tolerance synthesis and analysis for similar products. The 3D uncertainty cloud produced during large volume laser tracker measurement uncertainty estimation has the potential to overlay preliminary CAD design models to highlight areas of assembly process capability. For example, using the NPL laser tracker simulator [61] within the optimisation algorithm [51], the estimated laser tracker uncertainty can be plotted on to a 3D CAD model as shown in Figure 21. The stars represent the laser tracker positions and the black and red ellipses show the uncertainty cloud overlaying the CAD model.

2.4. Tolerancing

Within the previous sections, design and measurement methods within the aerospace industry were explored. This was followed by a review of tooling and assembly techniques for large volume aerospace structures, which identified the need for allocating capable tolerances. The following section investigates methods for tolerancing and relates them back to large volume aerospace structure design and assembly. The methods discussed within this chapter form the basis for proposals in later chapters relating to the secondary research aim (see Objective 1 Section 1.4) and the formation of the DfV guidelines in Chapter 4.

2.4.1. Tolerancing Overview

Tolerance allocation is a critical process for successful design engineering in the manufacture of aerospace structures. The purpose of assigning geometrical tolerances is to allow a permissible degree of error within the manufacturing process of the product, which will inevitably be present within any manufacturing system in one form or another. One of the key qualification tests for tolerance design is based on the measurability of the product in relation to the defined datum structure. Tolerancing of high value, complex products can be highly challenging when considering the stack-up of errors that accumulate from processes throughout the entire production of a single product [10]. This is further complicated when considering large assemblies and how the component variation will affect the overall dimensions of the end assembled product. A common engineering method for tolerancing is to use historical measurement data to build a process capability model for specific applications and apply a specified coverage factor. Process capability (C_p) is defined as:

$$C_p = \frac{USL - LSL}{6\sigma} \tag{8}$$

Where *USL* and *LSL* are the upper specification limit and lower specification limit respectively and σ is defined in (9).

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \tag{9}$$

Where μ is the mean of the measured samples $x_1, x_2 \ldots, x_N$.

Tolerances are often calculated as 3 σ to give a confidence interval of approximately 99.7% [1]. Processes do not often result in a mean value that lies on the centre between the upper and lower specification limits. A shift in the process distribution is typically observed due to a variety of reasons such as highly controlled parameters within one stage of the process chain alongside processes which are less controlled, possibly due to reduced knowledge of a particular activity within the process chain. The process capability when there is a shift in the normal distribution is calculated as in (10).

$$C_{pk} = min\left(\frac{USL - \bar{x}}{3\sigma}, \frac{\bar{x} - LSL}{3\sigma}\right) \tag{10}$$

This analysis method is not always possible to utilise within aerospace design due to the low rate of production, creating an incapability to generate a reliable standard deviation and subsequent realistic capability data [10]. The expense to not achieve RFT manufacturing can cause a programme to be at risk of failure which has led design authorities to set unrealistic tolerances in order to avoid responsibility of such an event.

This next section reviews tolerancing methods against large volume metrology requirements to establish methods for defining realistic design tolerances prior to large component assembly where external tooling interfaces are used to position assembly key characteristics.

2.4.2. Geometric Product Specification

The Geometric Product Specification standards (GPS) are the current BS EN ISO standards for defining the maximum permissible degree of variation of a component by allocating the shape, dimensions and surface characteristics of the given component in a standard format. The standard format uses symbols to denote the type of tolerance being assigned to the feature [80],[81].

Datums are established within engineering drawings during the process of tolerance synthesis to define the location and orientation of the tolerance zone. A datum structure is of critical importance within tolerancing and metrology processes as it casts constraints upon methods for component measurement when assessing geometric deviation. Careful consideration should be taken when defining datum structures as the measurement system can become significantly limited if the datum has been poorly positioned.

2.4.3. Simulation-Based Tolerancing

Simulation-based design is becoming ever more critical within the aerospace industry during the Product Development Process (PDP) for de-risking product design for manufacture. Tolerancing of complex multi-stage assemblies can be very time consuming and costly. The integration of component variation algorithms, based upon predefined tolerance limits, directly within CAD environments, has aided in improved product functionality and reduced manufacturing costs. One such popular example within the aerospace industry for simulation based tolerancing is 3DCS. 3DCS is used directly within the CATIA v5 environment to run Monte-Carlo based simulations of manufacturing and assembly processes to determine the dimensional impact of individual component and assembly variation, based upon user input tolerance intervals [82]. This is a very useful tool for quickly identifying bottle-necks and estimated assembly failure rates with a predicted conformance probability. However, simulation-based design is only ever as good as the parameters that are put into the models and the algorithms that drive them [83].

Enhancing tolerancing simulations through individual knowledge and previous data of similar products can reduce the uncertainty of design-based simulations, however, if there is a distinct lack of available and reliable data, the simulation is fundamentally at best an educated guess. A typical approach to using statistical tolerancing simulation packages is to input known manufacturing capability of individual components to produce the resultant tolerance stack. This has not proved to be reliable within the spacecraft manufacturing industry as the achievable tolerances within assembly are solely driven by the jigs that are used to assemble them (Type 2 assembly). Statistical simulations can instead be performed on the assembly jigs themselves. The majority of assembly fixtures contain adjustable tooling pick-ups commonly set by a laser tracker. This process removes the assembly tolerance stack and becomes reliant upon the measurement accuracy of the metrology instrument and the capability of the operator to adjust a given tool [59]. A traditional tolerance simulation would have little significance for this process [84].

2.4.4. Measurement Informed Tolerancing

The allocation of knowledge based tolerances is one of the least well understood concepts in product design. It is believed that poorly designed tolerances is one of the major causes of scrap and rework [30]. Within aerospace tooling for Type 2 assemblies, it has been observed that this is repeatedly the case and the primary complaint from production [59]. Measurement planning, with associated uncertainty analysis, for Type 2 assemblies should occur before tolerances and datums are defined so as to ensure successful product verification upon final product assembly. This has been recognised as a key area which is not yet realised within aerospace industries [10]. The lack of understanding amongst core design teams of metrology instrument capability has historically led to the synthesis and allocation of unrealistic tolerances. The following lack of capability to prove product conformance to a satisfactory degree of confidence would become detrimental to any large volume aerospace manufacturer if a given customer were to question this.

The effect of the environment was previously discussed in relation to assembly planning and tool design (see Section 2.3.3.3). The effects that the environment has on large volume metrology instruments is significant and defines the extent to which a part can be measured within a defined confidence interval. Through effective measurement planning and uncertainty analysis within the early stages of product development, realistic tolerances can be allocated upon data driven results.

2.4.5. Observations

Tolerancing of large aerospace structures is a complex subject matter. The inability to apply tolerances based upon process capability due to unique one-off constructions as seen within the spacecraft industry, has led to the allocation of global tolerances that stem from an undeterminable and unjustifiable source. This problem has continued throughout the decades of spacecraft production, partly due to a lack of insight into tolerancing, but mostly due to the fact that, to date, on the whole it has worked. The typical response from flight physics and stress teams to the question, “how accurate should it be?” is “to the tightest tolerance it can be made”. The follow on determination within early stage design for how precisely it can be made based upon a metrological uncertainty analysis appears to be lacking.

Using measurement uncertainty estimation as a baseline, tolerancing engineers can compare measurement uncertainty with process capability for component manufacturing. A typical analysis within large volume aerospace communities would reveal that the measurement uncertainty dominates the accumulated error and can be regarded as the sole source of error within assembly processes. This is due to spacecraft assembly typically occurring within a temperature controlled environment with relatively low mass components, largely undistorted by gravitational effects. The tolerancing aspect within the DfV guidelines will aim to inform designers of the limitations that should be applied to the tolerances from the derived accuracy that can be attained through the early stage measurement uncertainty analysis. The assembly process accuracies are largely limited by the accuracies of the employed metrology systems. Altering tolerances can have significant impacts upon assembly processes and tooling requirements which is why it is essential that within DfV, tooling, tolerancing, assembly process sequencing and metrology process planning are considered in parallel.

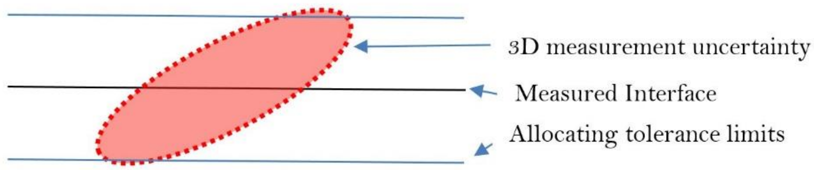


Figure 20: Measurement uncertainty simulation providing foundation for tolerance analysis and allocation for Type 2 assemblies when measurement uncertainty presents the major source for potential error.

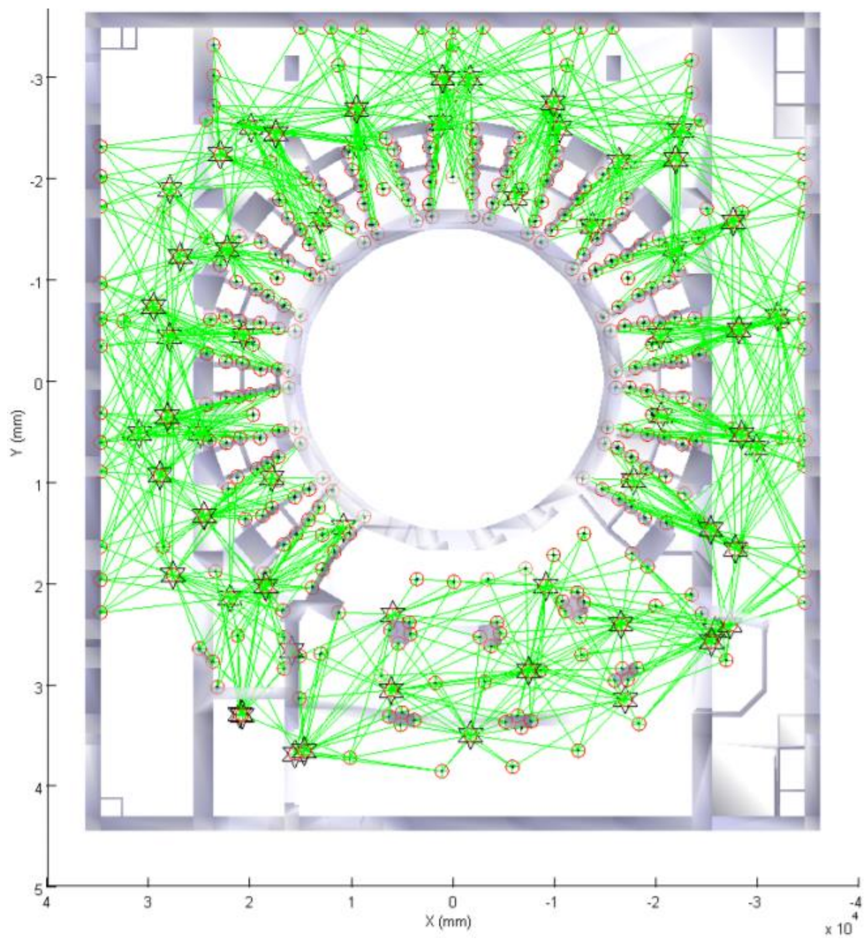


Figure 21: Laser tracker uncertainty estimation to feed back into early-stage tolerance synthesis and analysis [51].

2.5. Literature Review Summary

The literature review has revealed that geometric verification processes of aerospace structures are typically assessed through four key areas:

- Metology Processes

The methods in which large volume products can be measured can lead to significant variations in reported data. Early stage measurement planning is critical during the design stages as it impacts numerous assembly and manufacturing processes [85].

- Tolerance Drivers

Tolerances and geometry define the types of metrology systems required for application specific verification. Both Maropoulos et al. [10] and Morse et al. [86] described the importance of integrating large volume metrology instrument uncertainty analysis with tolerance limits allocation. There are in existence, many advanced methods for tolerancing. Therefore, within this thesis, guidelines are presented to inform tolerance synthesis processes of measurement uncertainty estimation to complement and guide existing tolerancing methodologies by placing constraints onto specification limits.

- Assembly Constraints

Complex assemblies with many components can have numerous potential manufacturing methods and assembly sequences. The effects of manufacturing and assembly sequencing are significant and can determine the outcome of a products conformance to specification. During and immediately prior to final assembly, aerospace products are generally geometrically verified at the sub-assembly stage prior to final assembly and then again following final assembly. The definitions of where to distinguish the sub-assembly stages are not always obvious and can impact end stage product conformance.

- Assembly Tooling Design

Successful large volume aerospace structures assembly is determined by the accuracy of the assembly tooling. The accuracy of the assembly tooling is defined by the way in which it is designed, commissioned and measured hence design for verification purposes and measurement uncertainty analysis is critical for successful RFT assembly [59], [63].

2.5.1. Areas for Further Consideration within DfV

In view of the above key areas, for the novel DfV methodology, it is proposed that:

A1. There is a need to introduce directly measurable assembly KCs at the design stage (see Objective 4 in Section 1.4).

A2. Assembly KCs for large (aerospace) structures need to be features measurable by large volume metrology instruments (see Objective 1 Section 1.4).

A3. Measurement features and systems for the assembly KCs need to be integrated within tooling structures for dimensional verification (see Objective 6-7 in Section 1.4).

A4. Assembly process and tooling design needs to be guided by measurement uncertainty constraints (see Objective 6-7 in Section 1.4).

A5. Tolerance design needs to be informed by estimated measurement uncertainty of the assembly process and large volume metrology instrument used for tool setting and product verification (see Objective 1-3 Section 1.4).

Chapter 3

State of the Art Industrial Scenarios

3.1. Overview

The ideas and case studies presented here are introduced to emphasise and further explore the areas of interest highlighted within the literature review summary to support and demonstrate the need for DfV. This chapter starts with a discussion of the expression of uncertainty in measurement using the GUM standards [38], which leads on to Monte-Carlo Simulation for uncertainty analysis. Three case studies are presented, the author was involved in all three and the experience gained influenced the proposal for the DfV guidelines. The first case study considers the manufacture of composite fan blades and the importance of embedding measurable KCs is derived. The second case study is related to the optimisation of the position of laser trackers, this illustrates the need for tolerances based on estimated measurement uncertainty. The final case study deals with the manufacture of a composite wing section and again the importance of KCs and tolerancing is apparent.

3.1.1. Guide to the Expression of Uncertainty in Measurement

One of the most common approaches to calculating measurement uncertainty is the GUM method. The equations for calculating the combined uncertainty (U_c) of a measurand Y from N other quantities $X1, X2 \ldots X_N$ using the GUM method through a functional relationship:

$$Y = f\,(X1, X2 \ldots X_N) \tag{11}$$

$$U_c = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 U^2(x_i)} \tag{12}$$

- $u(A) = 0.01$mm

- $u(B)$ = 0.01mm
- $u(C)$ = 0.01mm

Taking the values from Figure 4, the standard uncertainty of the spacecraft assembly can therefore be estimated as approximately 0.0173mm. It can be observed that when estimating assembly variation with standard uncertainties, the GUM approach simplifies to the common Root Sum Square (RSS) equation [38].

3.1.2. Monte Carlo Simulation

An alternative to the GUM approach is the Monte Carlo Simulation (MCS) method. This is a sampling based statistical approach. As opposed to the propagation of discrete measurement uncertainties through the root sum square (RSS) method observed within the GUM technique, the MCS model numerically generates large data sets using inbuilt random number generators to simulate a distribution [23]. This method relies upon the random number generator being truly random, which varies depending on the software used. As a result of the large simulated data set, distributions can be propagated as opposed to the single value standard uncertainties as in the GUM approach. The uncertainty of the final assembly can then be calculated from the resulting distribution. The central limit theorem states that as distributions of differing shapes are combined, the resultant distribution will tend towards a normal distribution. The shape of the distribution reveals the integrity of the measurement method and therefore the data provided from the MCS approach can provide additional benefits over the GUM approach as the distribution shape can be examined. For comparison, the example shown within Figure 4 was also solved utilising the MCS method using the engineering mathematics software Matlab. The computer code used to calculate the MCS for the spacecraft assembly uncertainty propagation within Matlab was:

1. *t = cputime;*
2. *P = 1000000;*
3. *A = randn(P,1).*0.01;*
4. *B = randn(P,1).*0.01;*
5. *C = randn(P,1).*0.01;*

6. *Y = A+B+C;*
7. *Uy = std(Y);*
8. *e = cputime - t;*
9. *histogram(Y);*

(13)

1,000,000 randomly generated data samples for *A*, *B* and *C* were substituted into the measurement model, thus producing a set of *Y* values, displayed in the histogram, shown in Figure 22. The standard deviation for the generated distribution yields $u(Y)$ = 0.0173mm. For this simplified example, it can be shown how the GUM and MCS approaches agree very well, however, the standard distribution value can vary using the MCS approach depending on how many samples are used and which random number generator is used.

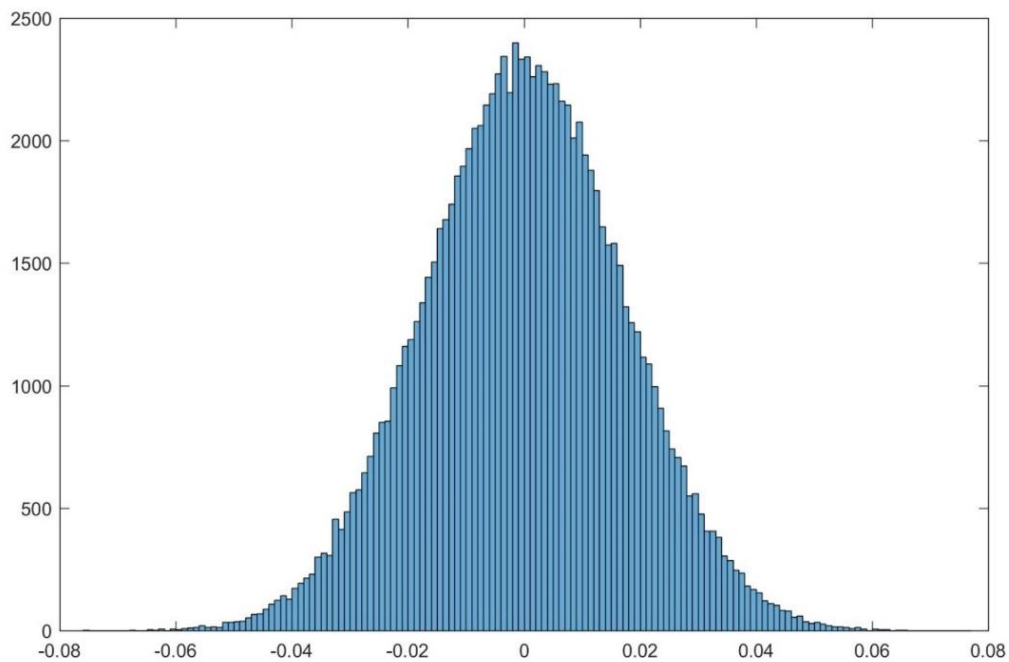


Figure 22: u(Y) – MCS histogram of distribution for example in Figure 4.

A *P* value of 1,000,000 points was used in the random number generator. The resultant distribution for $u(Y)$ is also dependent on the number of randomly generated data samples used within the distribution equation, as shown in Figure 23. The trend of the graph shows how the results converge as the sample size increases. This shows the importance of selecting the largest sample size possible taking into CPU time constraints. The CPU time, *(e)* of (13), to run the simulation for the given example using one million data points for each spacecraft cylinder took only 0.09 seconds. This example used is overly simplified, hence the short CPU time however, realistic computations are significantly more complex therefore it can be said that time for CPU calculations will increase with computationally demanding measurement simulations. For this reason, it is necessary to weigh the benefits of GUM and MCS approaches prior to analysis based on the application specific requirements. The computer code used to generate the graph in Figure 23 can be seen within (14).

```
M = [];
for P = 1:100000
A = randn(P,1).*0.01;
B = randn(P,1).*0.01;
C = randn(P,1).*0.01;
Y = A+B+C;
Uy = std(Y);
M (end+1) = Uy;
end
semilogx(M);
```

(14)

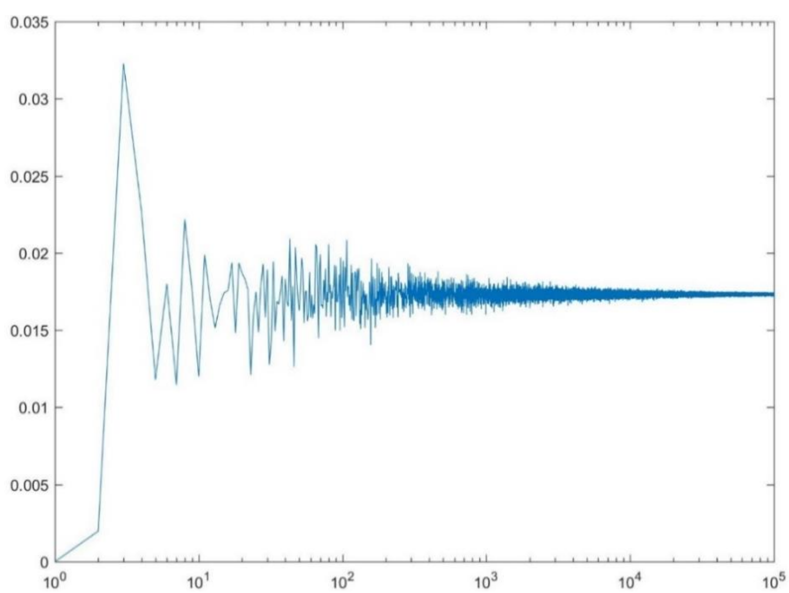


Figure 23: Number of samples vs. variability of MCS data.

3.1.3. Case Study 1: Composite Fan Blade Manufacturing

The aerospace industry has been working towards reducing the weight of aircraft by replacing metallic components with lightweight composite materials. One such target application is that of engine fan blades. Aerospace industries within the UK are seeking to develop innovative composite fan blades as part of an effort to save costs by reducing aircraft fuel consumption. It is estimated that fuel consumption reduction could exceed 20% with the new advanced engine design, aided by the weight saving achieved through the introduction of composite fan blades and cases [87]. To put this in perspective, within the year of 2012, US airliners spent $54,968,000,000 on fuel alone. The advanced engine design could have created an estimated cost saving of approximately $10,993,600,000 during that year. Considering the saving potential, the UK government is funding composite technology hubs with the aim of further developing technologies to introduce composite fan blades and casings [87],[88]. Aerospace engines are designed to tight tolerances as they are subject to extreme forces and high thermal loads. Material science and stress analysis is of high importance during design of aero engine components for these reasons. Composites pose challenges when trying to achieve tight geometrical tolerances. Ways in which carbon fibre behaves during cure cycles is difficult to model for complex shapes and adds an element of uncertainty to structural integrity. For this reason, a leading aerospace manufacturer developed an invar autoclave cure tool for composite fan blades with high strength and low CTE to reduce feature variation during temperature curing. To understand the capability of the tooling, the author designed an experiment to assess the geometry of the tool at various temperatures throughout the cure cycle. To achieve this, three separate metrology systems were employed:

1. A FARO Vantage laser tracker was used to create the high accuracy reference network as seen in Figure 24.

2. An articulated arm coupled with a scanning head was used to reverse engineer the surface of the invar tool to align the CAD with the reference network to provide the

photogrammetry measurements with a point of reference when measuring using the split bearing SMRs (SBRs) as seen in Figure 25.

3. An AICON 3D Systems GmbH photogrammetry system was used for the non-contact measurement of the surface profile as seen in Figure 26. Retro-reflective targets were used to reduce noise within the measurement data and also due to their high temperature resistance capability. Removable SBRs were positioned into the SMR nests during measurement. The invar tool was extracted from the autoclave and measured when it reached temperatures of 100℃, 140℃ and 180℃.

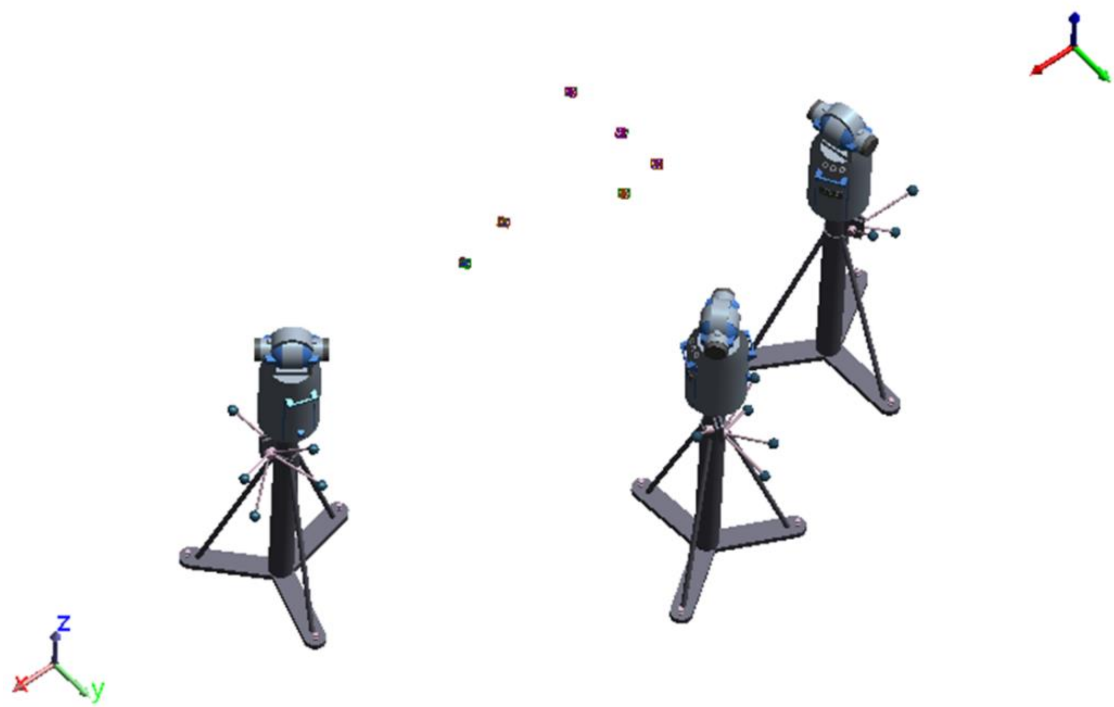


Figure 24: Multi-station, high accuracy laser tracker reference network.

A bundle adjustment tied the data sets together so that an analysis could be conducted. The dimensional positions of the individual targets were mapped during the curing cycle at the three temperatures previously listed and compared against the nominal CAD geometry, which acted as a baseline.

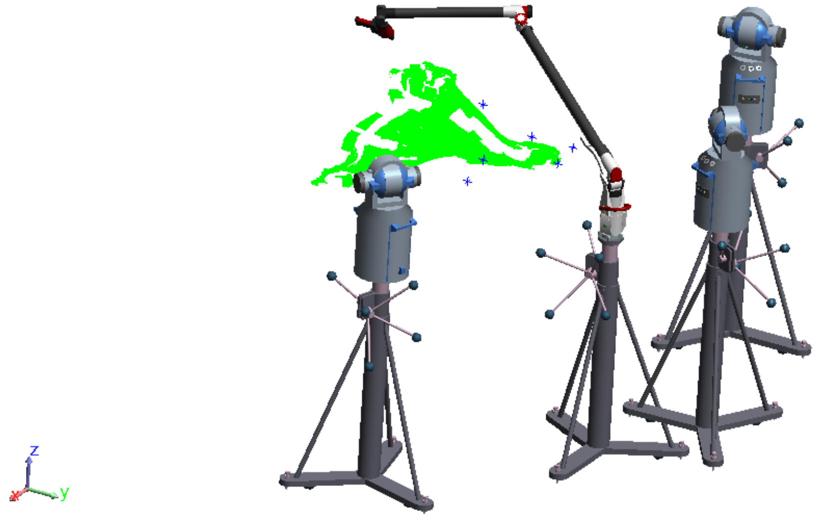


Figure 25: Laser scanning the invar tool surface for CAD alignment using a ROMER articulated measurement arm coupled with a CMS 108 scanning head.

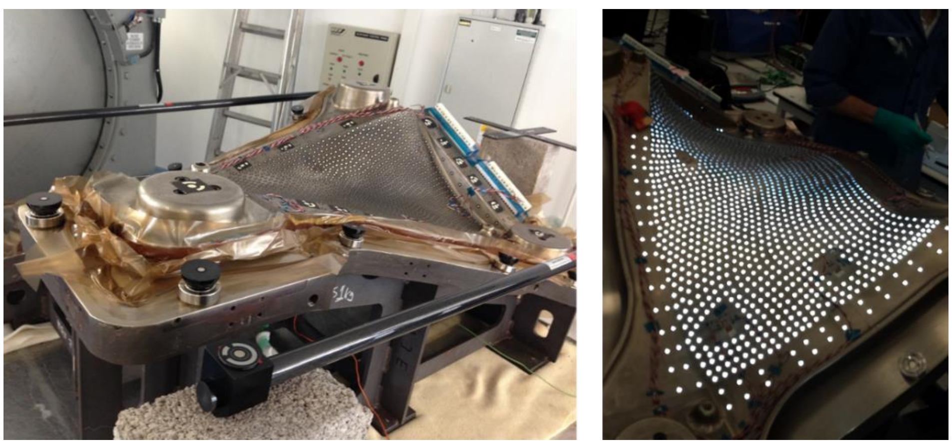


Figure 26: Invar autoclave tool for the composite fan blade.

The results revealed the areas most effected by thermal distortion as seen within Figure 27. The lower most part of the tool has expanded in excess of 1.5mm between 100°C and 180°C. The data obtained from the measurements were used to improve the tooling in the regions which experienced the most distortion. Whilst the measurement data provided useful vector plots, it failed to portray a meaningful traceable result due to the tool design.

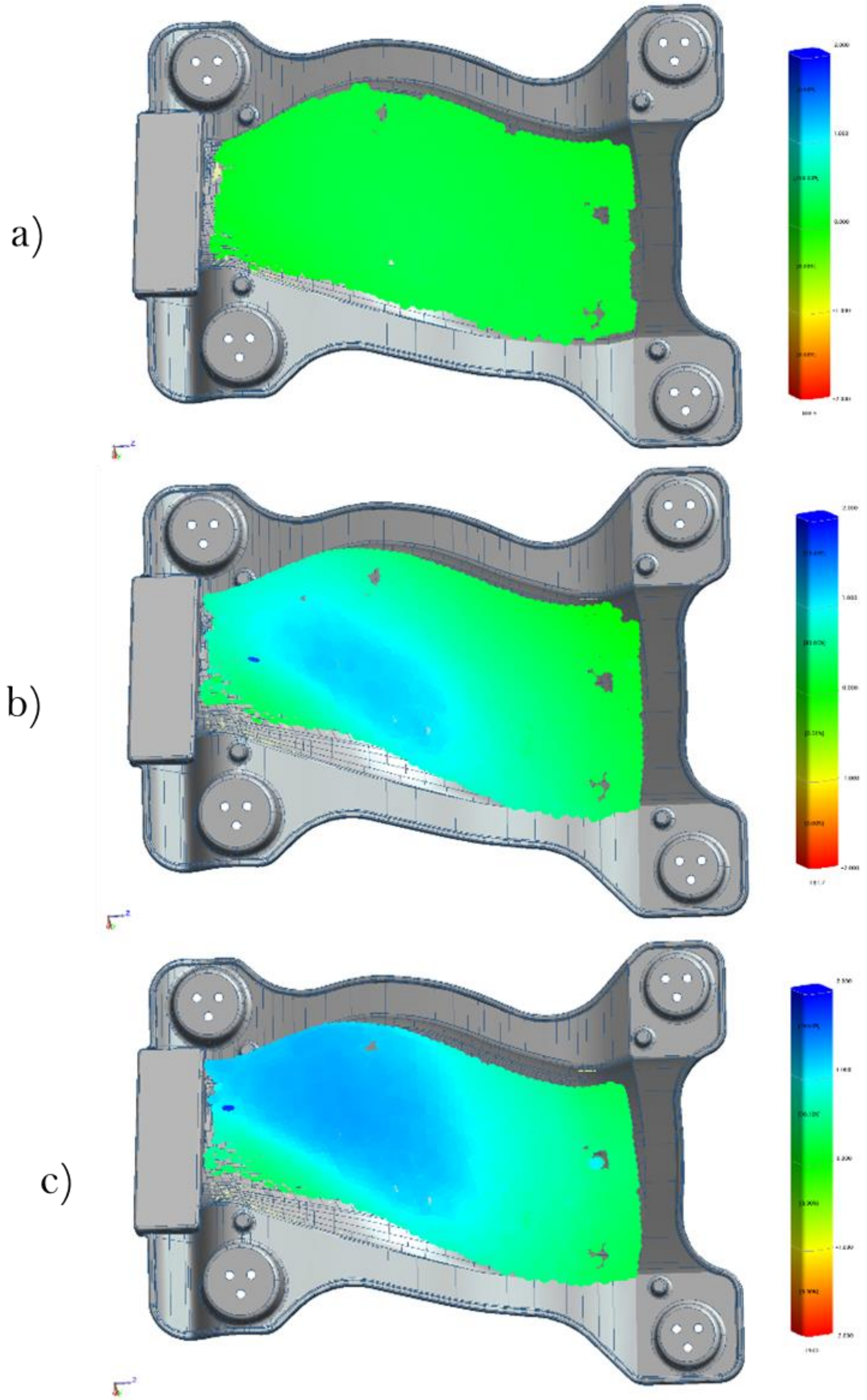


Figure 27: Composite fan blade autoclave tool - photogrammetry measurements taken at a) 100℃, b) 140℃ and c) 180℃. Vector plot scale ± 2mm.

3.1.3.1. Case Study 1: Discussion

Often observed within aerospace product design, metrology and product geometrical verification are left as an afterthought. Within this case study, the autoclave tooling was designed with an insufficient datum structure for the required verification task. The datum structure had to be indirectly referenced through best fitting the laser scanned complex surface geometry to CAD, resulting in an unknown and unquantifiable uncertainty source due to the lack of directly measurable KCs. As a result, the measurement data could not be readily interpreted with an acceptable degree of confidence as it could be made to fit a variety of solutions depending on the data fitting methodology. The result, due to the lack of consideration for verification during the design phase of the invar cure tool, has been a significant cost and time increase from the original project plan.

Photogrammetry can be a powerful tool for high density point measurement and rapid verification when used correctly, however, a degree of consideration is essential during the product design stage if it is to be utilised effectively. The requirement to dimensionally assess aerofoil profiles is common amongst various industries and there are few metrology instruments that are capable of achieving this task within typical aerospace volumes and specifications. It has therefore been observed that during the assembly and manufacturing process planning, KCs must be identified by the design team and designed with a degree of measurability suitable for the appropriate metrology system. This is especially critical with manufacturing challenges such as the composite fan blade case study as the verification requirements are at stages where further limitations are placed on the metrology system due to the environmental conditions in which the products are to be measured. It is therefore critical that environmental conditions are mapped against staged assembly processes and verification requirements.

3.1.4. Case Study 2: Laser Tracker Position Optimisation

Prior to the final assembly of aerospace structures, final assembly jigs, designed to hold components in their nominal design positions, are set and commissioned with the use of laser trackers. Fixtures are designed to pick up on key features of a product to ensure accurate component alignment. Due to the scale of aerospace final assembly fixtures, tooling pick-ups are designed with a level of available adjustment so that they can be adjusted relative to a global reference frame.

Learning from individual knowledge and practical work undertaken within aerospace industries, the standard procedure for setting an aerospace fixture is:

1. Distribute SMR drift nests across fixture. Fix drift nests with the use of adhesive or mechanical fasteners to ensure minimal movement during measurement.
2. Locate laser tracker so that it has an optimal line of sight to the drift nests, as well as the points of interest on the fixture for interface setting.
3. Measure the drift nests in relation to know fixed locations on the fixture to position the assembly datum.
4. Locate the drift nests within the CAD model of the fixture through an iterative process to ensure good alignment to the nominal datum structure.
5. Locate the laser tracker in relation to the global coordinate system using the measurements of the drift nests through iterative best fit functions.
6. Measure the points of interest on the pick-ups and align the adjustable fixture interfaces to nominal.

The challenge faced with this approach is the stack up of uncertainty that is incurred. Considering steps 7-10 of the PUMA part 2 process (see Section 2.2.2.5.1), the measurement uncertainty can be estimated prior to conducting the task. Preceding measurement of the tooling pick-ups, there is an identified stack up of uncertainty inherent within the process. Each of the following processes are dominant sources within an uncertainty budget for laser tracker measurement:

a) Measuring the reference network of drift nests.
b) Aligning the reference network within the nominal CAD model.
c) Locating the laser tracker within the created reference network of drift nests.

Through the optimisation of process a) the overall measurement uncertainty can be significantly reduced, following the guidelines laid out within Figure 17. A software simulation was undertaken to estimate the benefits of optimal laser tracker positioning. The method for testing the concept is:

1. Locate single laser tracker at a position of 1m away with azimuth and elevation angles set to 0˚.
2. Simulate 1000 point measurements utilising a Spatial Analyzer laser tracker uncertainty model and calculate standard deviation of measurement error.
3. Repeat Step 2 with additional laser tracker stations including 2, 3, 4 and 5 positions.
4. Repeat measurement process steps 1 to 3 with laser tracker station distances of 3, 5, 10 and 35m.

The process above was conducted three times to improve the confidence in the uncertainty estimations. The results were tabulated as shown within Figure 28 and graphically illustrated as shown in Figure 29. The five laser tracker station positions for the studies are illustrated in Figure 30.

1m Station Distance

Stations	Test	Std (mm)	Average (mm)
1 Station	1	0.0111	0.0109
	2	0.0106	
	3	0.0112	
2 Stations	1	0.0081	0.0080
	2	0.0078	
	3	0.0081	
3 Stations	1	0.0067	0.0066
	2	0.0065	
	3	0.0066	
4 Stations	1	0.0058	0.0057
	2	0.0060	
	3	0.0054	
5 Stations	1	0.0052	0.0051
	2	0.0050	
	3	0.0050	

3m Station Distance

Stations	Test	Std (mm)	Average (mm)
1 Station	1	0.0235	0.0234
	2	0.0241	
	3	0.0226	
2 Stations	1	0.0168	0.0169
	2	0.0166	
	3	0.0172	
3 Stations	1	0.0137	0.0137
	2	0.0137	
	3	0.0136	
4 Stations	1	0.0117	0.0119
	2	0.0120	
	3	0.0122	
5 Stations	1	0.0106	0.0107
	2	0.0106	
	3	0.0108	

5m Station Distance

Stations	Test	Std (mm)	Average (mm)
1 Station	1	0.0368	0.0370
	2	0.0369	
	3	0.0374	
2 Stations	1	0.0263	0.0262
	2	0.0255	
	3	0.0267	
3 Stations	1	0.0208	0.0213
	2	0.0214	
	3	0.0216	
4 Stations	1	0.0186	0.0186
	2	0.0188	
	3	0.0185	
5 Stations	1	0.0166	0.0167
	2	0.0169	
	3	0.0165	

10m Station Distance

Stations	Test	Std (mm)	Average (mm)
1 Station	1	0.0699	0.0711
	2	0.0703	
	3	0.0731	
2 Stations	1	0.0509	0.0507
	2	0.0500	
	3	0.0511	
3 Stations	1	0.0403	0.0401
	2	0.0402	
	3	0.0400	
4 Stations	1	0.0345	0.0348
	2	0.0349	
	3	0.0350	
5 Stations	1	0.0315	0.0316
	2	0.0316	
	3	0.0318	

35m Station Distance

Stations	Test	Std (mm)	Average (mm)
1 Station	1	0.2352	0.2383
	2	0.2395	
	3	0.2401	
2 Stations	1	0.1676	0.1687
	2	0.1703	
	3	0.1683	
3 Stations	1	0.1387	0.1392
	2	0.1391	
	3	0.1397	
4 Stations	1	0.1253	0.1234
	2	0.1217	
	3	0.1232	
5 Stations	1	0.1100	0.1084
	2	0.1086	
	3	0.1067	

Figure 28: Tabulated results of simulated laser tracker measurement error estimated at a measured distance of 1m, 3m, 5m, 10m and 35m, with 1 to 5 measurement stations.

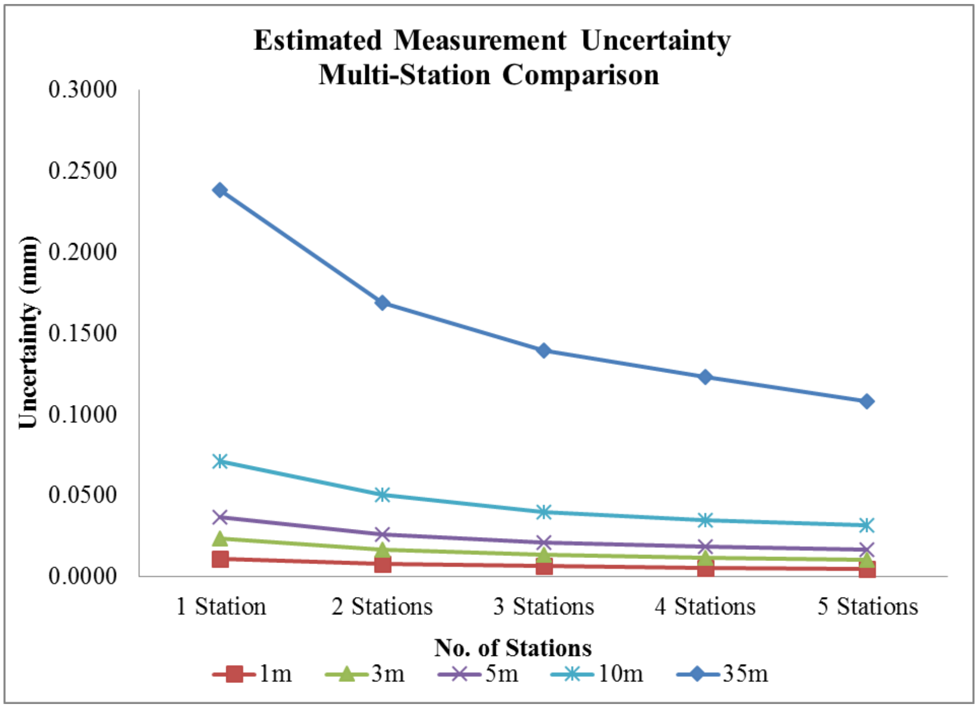


Figure 29: Graphical illustration of simulated laser tracker measurement error estimated at a measured distance of 1m, 3m, 5m, 10m and 35m, with 1 to 5 measurement stations.

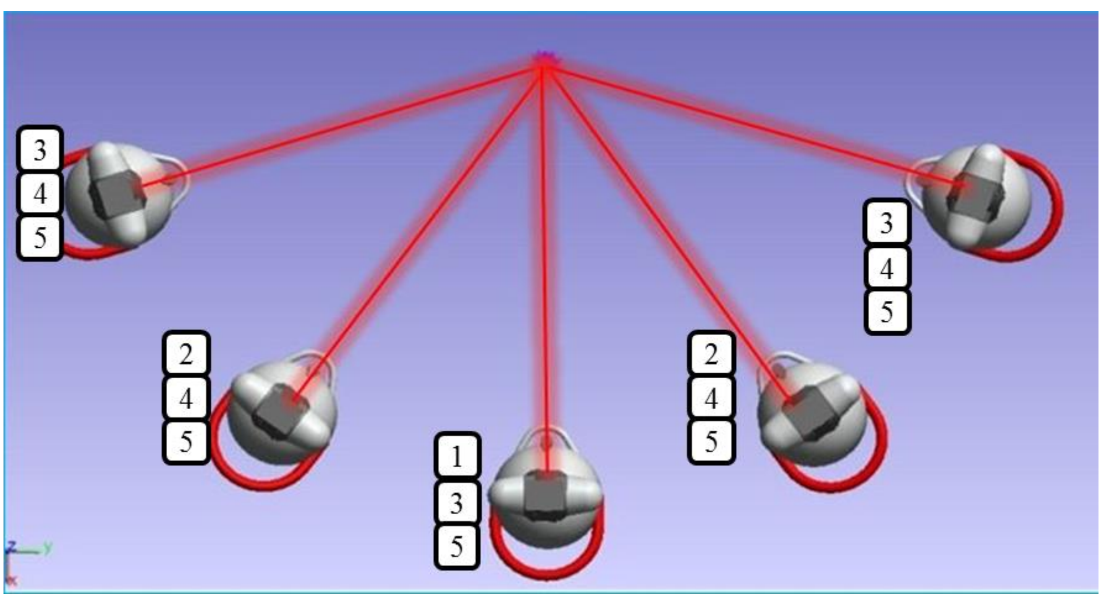


Figure 30: Laser tracker positions for multi-station comparison. The numbers depict which station was used during the trials i.e. where there is a number 3, the corresponding tracker station was used for the 3 station study.

3.1.4.1. Case Study 2: Discussion

The results revealed that adding additional stations can significantly reduce the estimated laser tracker measurement uncertainty. As can be seen in Figure 29, the benefits of adding additional laser trackers decreases with additional each station. It can be seen that the further the measured distance, the greater the uncertainty reduction becomes from adding additional stations. Laser tracker set up times can be lengthy therefore a trade-off between required measurement uncertainty and cost needs to be undertaken when determining the optimal number of laser tracker stations for the application specific verification task.

The simulation process proved to be a useful tool for designers when allocating tolerances. After tolerance design, measurement simulation can be used as a means to validate the practicality of the allocated tolerances to generate an estimate of the confidence to which the product can be verified against. Within the spacecraft manufacturing industry, final assembly variation is driven by laser tracker measurement error due to the tight tolerances specified for critical interfaces over large volumes. As spacecraft have a low rate of manufacture, a scrap assembly cannot be afforded so it is essential that within the design stage, these factors are considered and analysed.

3.1.5. Case Study 3: Composite Wing Section Manufacturing

The most dominant customers within the commercial airline industry are now demanding a reduction in fuel costs. As aircraft manufacturers do not control the price of fuel, they are looking to innovative methods for increasing the fuel economy of their products. A key factor identified for the increase of fuel efficiency is to reduce aircraft weight. To enable this, manufacturers are looking to alternative materials and methods for manufacturing wings. A conventional wing assembly for the A320, can be seen within Figure 31. The assembly process for the A320 wing is a complex multi-stage operation with a majority of the large volume components being aluminium alloys. A significant portion of the weight is within the wing covers, stringers and spars. The primary aim was to develop manufacturing methods for an integrated cover, stringers and spar product composed entirely of carbon fibre as illustrated in Figure 32. The program advanced automated fibre placement (AFP) technologies within the UK and led to further government investment to spearhead the research, involving partners including GKN Aerospace and Spirit Aerosystems UK.

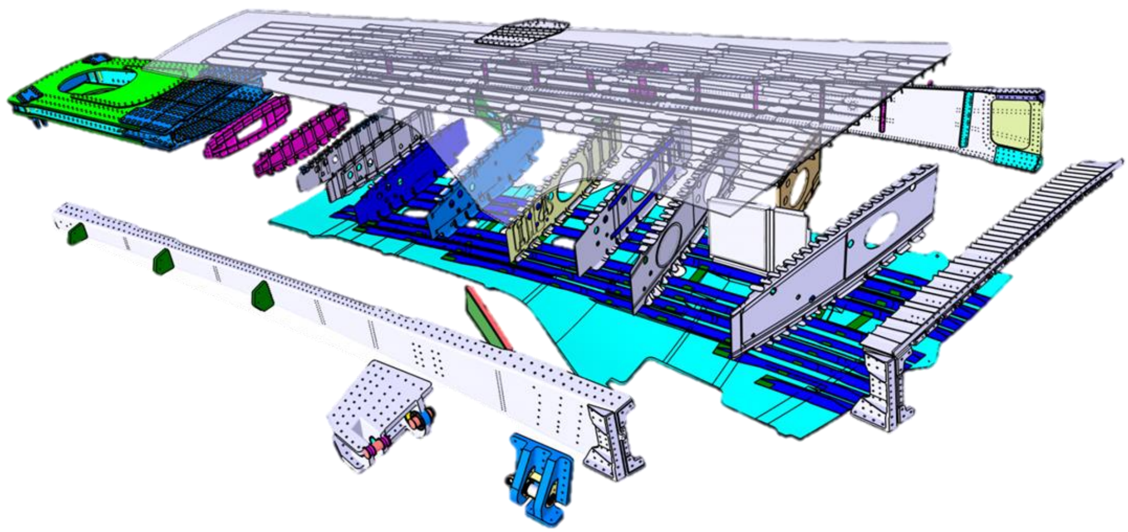


Figure 31: A320 wing exploded view – conventional design.

When the wing-box project was first initiated, there was no knowledge base on how accurately an integrated composite wing-box wing design could be manufactured or what the best manufacturing method could be. For this reason, existing aluminium wing build tolerances were erroneously applied and a decision was made to measure the trial wing-box structures following manufacture to determine future tolerance capabilities.

The wing-box was designed within CAD to fulfil the criteria of an existing wing structure section, illustrated in Figure 32. The layup tooling was designed around the wing-box CAD model and knowledge of current AFP technologies. As a result, 8 wing-box variants were designed and manufactured using SoA processes and manufacturing systems.

Following manufacture of the wing-box structures, they were tested for structural flaws via NDT processes to assess the capability of the AFP techniques. After the refinement of this process, the wing-box structures were sent for geometric verification.

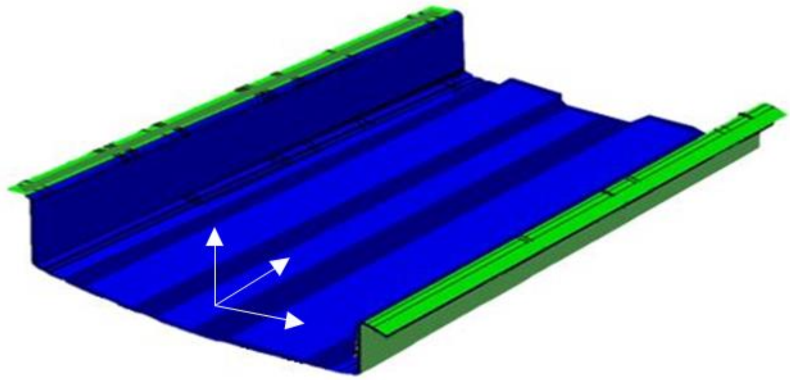


Figure 32: Wing-box fully composite wing, unconventional integrated design.

At this stage, it was observed that a local datum structure, or measurement methodology, had not been considered. Measurement of freeform surfaces presents many challenges. Freeform surfaces, commonly referred to as complex or sculpted surface, are defined within ISO 17540-1:2007 as “a complex feature with no invariance degree” [89]. Hard datum features on large products will typically consist of either planes, cylinders or a combination of both. Freeform surfaces are not axis-symmetric like planes or cylinders which makes them very challenging to datum onto. The ISO GPS standard permits profile tolerances to be applied to freeform surfaces, however, there does not exist a standard for the measurement of freeform surfaces such as there is for flatness, straightness, cylindricity and roundness [90]–[92]. The white reference frame, seen towards the root end of the wing-box, Figure 32, was added at a later date for the purpose of measurement trials and there was no direct method for measuring the reference frame due to the inherent spring-back associated with carbon fibre U-shaped structures. As a result, the measurement process took to an iterative, weighted best-fit of laser scanned measurement data to determine the agreement of the manufactured wing-box product to the CAD design. This process incurs multiple additional sources of random measurement error that made it impossible to cost-effectively calculate a realistic uncertainty value for the measurement data. In turn the manufacturer were unable to derive data driven manufacturing tolerances for future wing-box products based upon traceable measurement results.

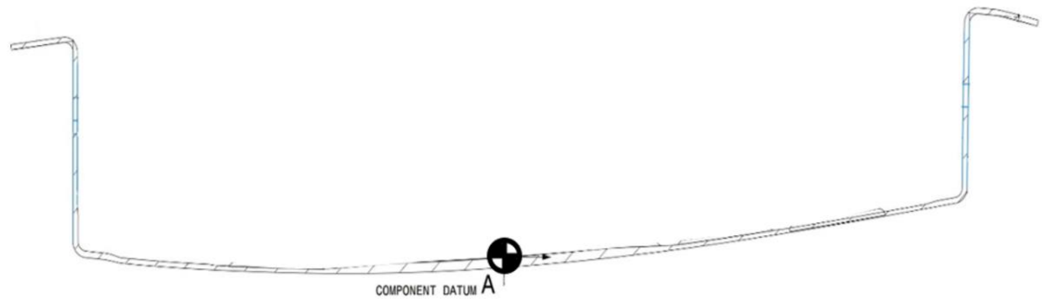


Figure 33: Wing-box datum structure for measurement and tolerancing.

3.1.5.1. Case Study 3: Discussion

Through this case study, a lack of universal standards for best practice of measuring freeform complex surfaces became evident. Measurement of such surfaces is common within the aerospace industry as meeting profile tolerances for aerofoil surfaces can be critical in order to validate that aerodynamic requirements can be maintained so measurement uncertainty analysis needs to be conducted prior to defining tolerances. Whilst there is no recognised standard for this measurement procedure, it can be argued that there are best practice principles that can be applied to significantly reduce the load on data interpretation and analysis following surface measurement during product design. For the given case study, little in the way of datums was considered during the manufacturing design. Whilst manufacturing with carbon fibre presents challenges in maintaining form post cure-tool removal, research is continuing to understand and more accurately predict structure deformation following the cure cycle [93]. This presents potential opportunity for identifying areas of maximum stability for the design of embedded KCs specific to the selected metrology system for verification. The features can be inserted during the manufacturing stages to enable controlled data fitting of measurement points to nominal CAD surfaces post manufacture.

Chapter 4

The Design for Verification Framework

The DfV framework was created through observations made through the literature review as well as individual knowledge gained during practical exercises with experts in the field of large volume metrology for aerospace. Much of what is learnt within the aerospace industry relating to use of large volume metrology systems is through individual knowledge and cannot be learnt through published best practice guides or other literature. This has rendered challenges with respect to supporting claims with references.

The research methodology used for forming the guidelines has followed the skeleton process for research within engineering design defined within 'The Craft of Research' [94] and illustrated within Figure 34. The practical problem, research question, project and response are further detailed within the following sections. The practical problem was recognised as a gap in the knowledge and has such lead to the creation of the DfV guidelines.

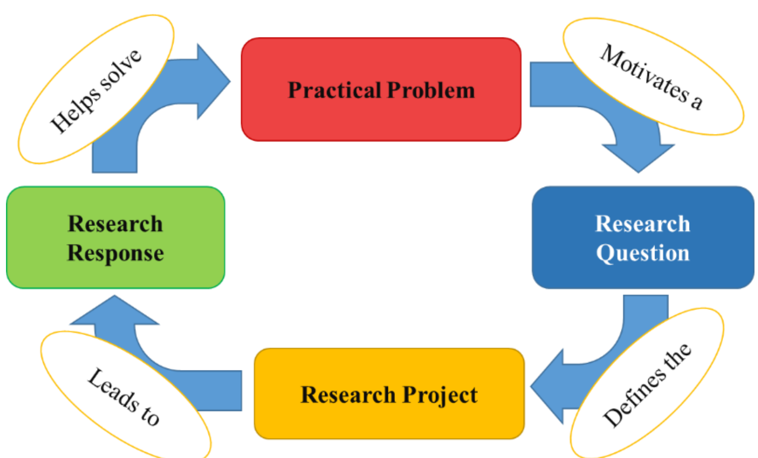


Figure 34: The process of research in engineering design, available from: 'The Craft of Research [94].

4.1. Research Methodology

The research methodology employed to form the framework for DfV is common within engineering design challenges. The design guidelines have been viewed as design challenges in their own right and developed as such. The framework is built upon defined measurement uncertainty quantification principles documented within engineering standards, highlighted within the literature review.

4.1.1. Practical Problem

The research problem was identified through a collaborative work package led by the author between the University of Bath and ADS. The problem was further demarcated as a gap within knowledge through SoA literature findings and personal experience within aerospace manufacturing facilities. During work with ADS, the author recognised a distinct lack of consideration for adequate metrology instrument use within the design phases of spacecraft development. That is to say, during the early stage design phases, dimensional verification methods were not clearly defined or understood and there were no guidelines to assist the designer in designing features for dimensional verification and how that can both influence and benefit product, assembly and tooling design. It was observed that this led to incapable measurement procedures resulting in misalignments and non-conforming products due to the low statistical confidence in the measurement procedures. A large percentage of knowledge surrounding the use of large volume metrology instruments is gained through on-the-job training and learning from other experts in the field. This continues to create challenges for designers in defining appropriate verification techniques as there is limited published knowledge and as such, pertinent questions are not being addressed within the early design phases.

4.1.2. Research Questions

The research questions, as declared in Chapter 1, are fundamentally based upon the formation and testing of the DfV guidelines. The successful response to the secondary research questions b) and c) are dependent upon the effective implementation of the primary research question a). The aims, also detailed in Chapter 1, outline the targets for the DfV framework to incorporate methods for the seven listed objectives. The robustness of the proposed DfV framework solution needs to be tested against intended purpose and target application. To accomplish this, it is applied to a spacecraft design and assembly example in Chapter 5 and Chapter 6.

4.1.3. Research Background and Overview

The research targeted RFT assembly of large volume aerospace structures using metrology instrument uncertainty to guide design rules during the latter phases of early stage design. The formation of the DfV guidelines prompted a technology demonstrator to be designed and constructed using the proposed DfV process so that the guidelines could be assessed through quantitative means. The method for generating quantitative data and assessing the process was to closely mimic a real-world scenario where a high value aerospace structure was required to be manufactured RFT to demanding tolerances without prior knowledge of process capability data. The guidelines were constructed upon structures of existing design process flows observed through literature reviews and industrial collaborations. Learnings were taken from the case studies which demonstrated the need for an enhancement to the current design process and they were collated to form the basis of the guidelines, supported by the literature review. The guidelines were tested through practical implementation and quantitative assessment. The DfV guidelines were assessed through the method of comparison between an existing assembly process for spacecraft manufacture and the resultant process after applying DfV. A simplified CAD model for the E3000, which extracted all the key assembly features congruent with the likely design of the NEOSAT was created for the comparison. The existing assembly process for the E3000 was mapped against the NEOSAT CAD model whereby base-lining the existing process. The DfV rules were applied to the NEOSAT CAD model and the results were compared against the baseline model. This method allowed a direct comparison of design with and without the implementation of DfV within SoA aerospace manufacturing processes,

4.2. Proposed Design for Verification Framework

The early iterations of the DfV framework [3], Figure 35, were built upon a conglomeration of related research including the MPM, introduced by Maropoulos et al. [10] and the guidelines proposed within the IDVM framework by Muelaner et al. [64]. These methods were focused primarily with measurement planning and negated the adoption of metrology based knowledge as a feedback loop into early stage design to drive assembly sequencing and tooling design. To build upon these frameworks, the four primary areas that provided the foundation for DfV within the early iterations were:

1. Uncertainty based, metrology system specific tolerance analysis.
2. Optimisation of tooling for metrology specific requirement.
3. Enhanced assembly through advanced metrology specification.
4. Reduced measurement uncertainty and enhanced process.

The guidelines were poorly laid out and were found to be confusing by designers due to the lack of a clear sequential process to follow. This was compounded with an observed confusion about the terminology and phrasing within the guidelines. The guidelines were also found to be impractical as they failed to consider the competing DfX parameters and where they would fit within the overall DfX toolbox.

The final iteration of the proposed framework overview is illustrated in Figure 36. Steps 1 to 6 are the proposed existing design best practice route, previously disregarded within the early iterations of DfV. This was to satisfy the guidelines laid out by Huang et al. [31] which stated that a successful DfX tool should consider other competing DfX tasks with feedback loops. Although not fully encompassing and recognising that there is much detail that could be added to these steps, it is believed that within them is contained enough information to represent at which stage and where the author proposes to integrate the DfV guidelines and the DfV feedback loop into the other DfX parameters.

The area marked in the dashed red line, Figure 36, is the author's proposed contribution to knowledge where the designer is lead to optimise the product and process for DfV. For this reason, little explanation is given to steps 1 to 6 here; they are discussed in the literature [1], [28].

The DfV guidelines are divided into two sections, similar to how Huang et al. [31] recommended within the PARIX model. The products and resource are grouped into the streamlined DfV process encased within the green box whilst the interactions are clearly shown within the DfX section encased in the blue box, with 'X' being Verification in this instance. The interactions are represented as questions to the designer to generalise the process so that it is generic enough to be applied to any large volume product and process.

The overarching role of DfV within assembly process design is to consider the factors that affect verification during the assembly process and seek to minimise or optimise their effects through optimisation of assembly sequencing and processes based upon verification requirements. The overarching role of DfV within product design is to consider instrument specific features for strategic verification processes to ensure RFT manufacturing and influence assembly processes for improved conformance. These concepts were derived through the industrial scenarios, discussed in Chapter 3 and formed into the resultant guidelines to aid in overcoming the recognised shortfalls with current design practices detailed within each of the discussion sections within Chapter 3.

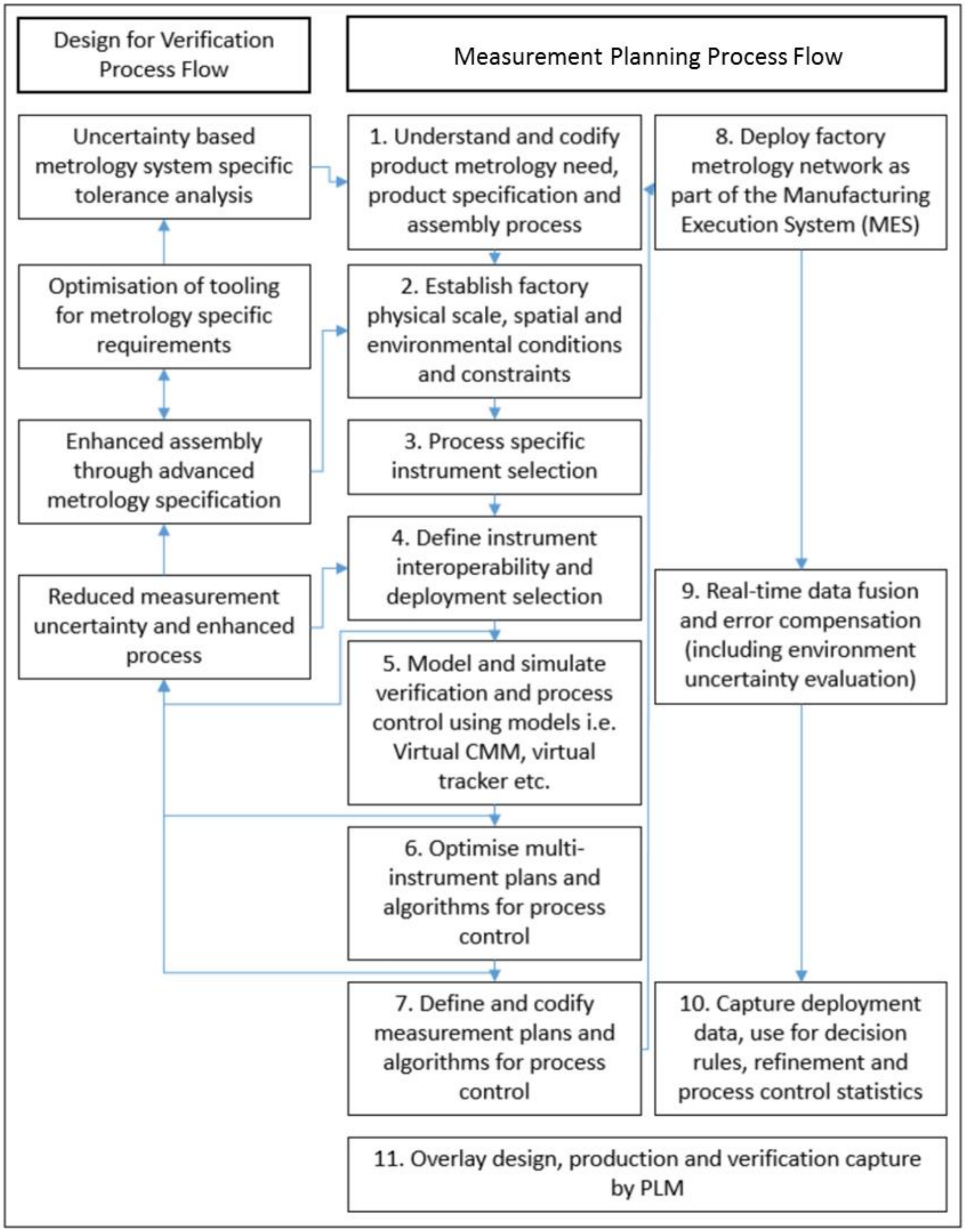


Figure 35: First iteration of the Design for Verification framework [3].

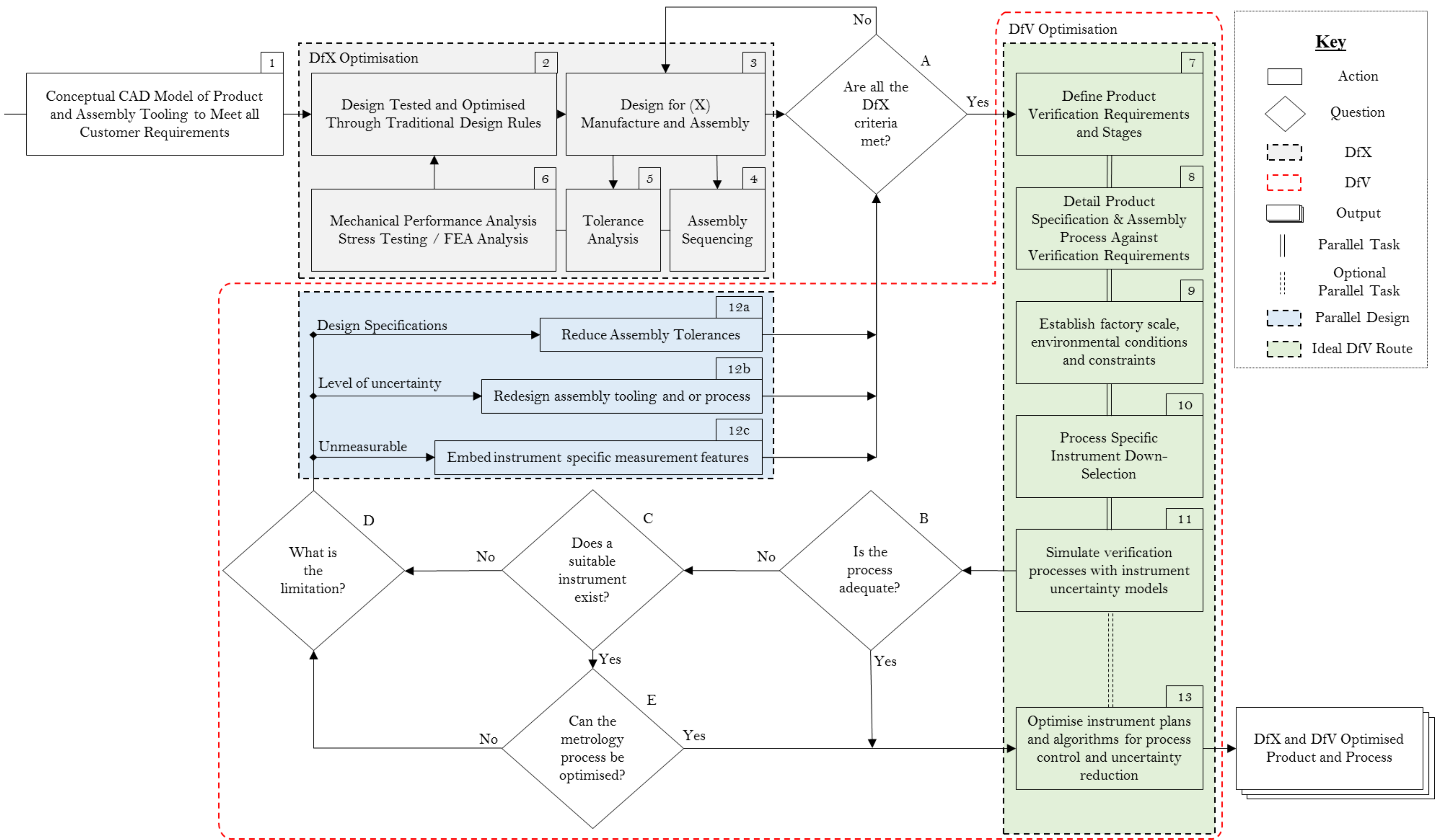


Figure 36: DfX and Proposed Design for Verification Framework.

4.2.1. Step 1: Conceptual CAD Model of Product and Assembly Tooling to meet all Customer Requirements

The framework overview starts at Step 1, a stage where the design has matured into a functional CAD model. Within the aerospace industry, conceptual designs for next generation aircraft or spacecraft begin with a vision that exists within the mind of the stakeholders, largely determined by aesthetic objectives. The vision is then interpreted by a design team and the PDP is initiated. Through design iteration, a drawing within the digital domain is eventually produced.

4.2.2. Step 2: Design Tested and Optimised Through Traditional Design Rules

The design is run through further iterations in Step 2 to ensure that all functional requirements are met whilst maintaining sight of the original design vision. The CAD model is matured and detail is added to demonstrate capability to meet customer requirements

4.2.3. Step 3: DfX - Manufacture and Assembly

At this stage, Step 3 shows how the design team is expanded to include specialist knowledge from production and flight physics. The criteria for manufacturability, assembly and X are traded off such that a compromise between all DfX streams are weighed and considered. The DfX parameters often present conflicting requirements and a medium is to be reached such that the original design intent is not compromised whilst maintaining functionality.

4.2.4. Steps 4-6: Simulation-Based Design Iterations

The Steps 4 to 6 are based around using simulation software to validate and verify the proposed design solution. Discrete event simulations (DES) are used for assembly sequencing to identify bottle-necks and identify opportunities for production optimisation whilst FE models are used for validating the mechanical performance of the product. A feedback loop has been included to highlight the necessity of revisiting the vision of the product that was agreed with the stakeholders. Following DfX, a design can become vastly different to that which was originally envisaged. A follow on decision box ensures that all the DfX requirements have been met which again includes a feedback loop to emphasise the iterative nature of design.

4.2.5. Step 7: Define Product Verification Requirements and Stages

(See A2 and A5 in Section 2.5.1)

Step 7 is the first stage within the proposed Design for Verification framework illustrated in Figure 36. The targeted application for DfV is final assembly of large volume, high value and low rate aerospace structures. Following successfully design of the product and ensuring that it meets all stakeholder and manufacturing requirements, the first exercise within the DfV guidelines is to establish an understanding of the predefined key characteristics of the end product. The proposed questions are:

Q1. What are the key features that need to be dimensionally measured to verify product conformance and functionality, i.e. hole position, planarity, overall dimensions?

This step relates to Objective 5 and Objective 6 in Section 1.4. Through the mapping and understanding of the verification requirements at each key assembly stage, the designer can be guided to optimise the assembly sequence and product design based upon the metrology instrument limitations. Cheng et al. [95] defined an inference engine to classify product measurability through feature-based analysis. The method classified extracted features into sub-groups through large volume metrology instrument measurement capability and limitations. This critical stage within the DfV framework immediately highlights design flaws that inform the designer on appropriate product features for integration to ensure product measurability.

Q2. At which stage do the components need to be dimensionally measured to validate product integrity during final assembly, i.e. are there critical features that need to be measured prior to follow on assembly operations?

The MPM introduced by Maropoulos et al. [96] illustrated the necessity to consider assembly sequencing in relation to measurement plans. The purpose of this stage is to understand the KCs for the assembly process flow and to map product verification requirements against the staged process, detailed alongside the assembly and tooling requirements.

4.2.6. Step 8: Detail Product Specification and Assembly Process against Verification Requirements

(See A2, A4 and A5 in Section 2.5.1)
Step 8 captures the product specifications. The design tolerances are listed against the verification requirements to form the basis for the instrument selection process. Feature specific tolerances are captured against geometrical constraints so that metrology system selection can be formed upon product specific requirements. This enables the consideration of feature based design to enable alternative metrology systems to reduce inspection timescales and costs.

This step relates to Objective 3 and Objective 7 in Section 1.4. Through detailing instrument measurement capability against product requirement, the designer is led to understand the relationship between confidence in measurement and product tolerances. The process of allocating capable tolerances with defined process capability is well understood. Tolerance analysis software such as 3DCS and CAPRAtol have been created to minimise assembly risk and cost whilst maintaining product functionality [30],[82]. It is important to state that the author is not proposing a novel tolerancing methodology but suggesting that consideration of the estimated measurement uncertainty should influence tolerance design allocation during early stage design to place constraints upon products and processes. Morse et al. [86]

highlighted the importance of linking tolerancing with large volume metrology instrument uncertainty. Where assembly accuracies for aerospace structures are largely limited by measurement uncertainty, it is proposed that the key driver for tolerance allocation within these circumstances should be based upon statistical measurement system uncertainty estimation modelling, such as the tool developed by Forbes [61] for laser tracker error quantification or PUNDITCMM for CMM uncertainty modelling [97].

4.2.7. Step 9: Establish Factory Scale, Environmental Conditions and Constraints

(See A2 and A5 in Section 2.5.1)
Step 9 raises awareness of how the factory environment can pose significant limitations on inspection processes. Thermal gradients and air flow significantly limit large volume metrology instruments and it is often too costly to introduce temperature controlled environments for large scale assembly. The alternative is to limit the extent to which the environment impacts the component assembly variation through data driven assembly sequencing. Factories can be known to be stable during certain parts of the day and can provide suitable assembly and inspection conditions. This can be used to guide designers to effectively plan the assembly sequencing so that down-time is reduced and parallel working can be maximised.

This step relates to Objective 2 and Objective 4 in Section 1.4. The environment has a significant effect upon measurement uncertainty which can be minimised through the introduction of self-calibrating tooling designed for integration with specific metrology instruments used for verification. Muelaner et al. [98] demonstrated the effects of the environment upon measurements and large scale assemblies showing how gravitational, thermal and refractive index changes within the measurement volume can significantly impair production capability. Through establishing the limitations of the assembly environment, the assembly tooling and sequencing should be designed to minimise these impacts.

4.2.8. Step 10: Process Specific Instrument Selection

(See A1, A2, A5 in Section 2.5.1)
In Step 10, the data collated and mapped within Steps 7-9 are used to select the potential metrology systems that could be utilised for dimensional inspection of the aerospace assembly at the required stages. This step is also driven by limitations within available hardware and the availability for capital expenditure on further metrology systems. Tools such as the instrument selection tool, produced by the LIMA group are useful aids to support this process [99].

This step relates to Objective 1 and Objective 7 in Section 1.4. Through the process of selecting an instrument based upon verification based requirements for successful assembly, the designer is quickly informed if the product is immeasurable based upon instrument availability and capability. The assembly features extracted within Step 7 need to be questioned at this stage to quantify measurement process costs against design limitations. Ferri et al. [100] demonstrated the need for an integrated large volume instrument database to build knowledge based instrument capability indices. Efforts to realise this are continuing with projects such as the 3DImpact-Online [101].

4.2.9. Step 11: Simulate Verification Processes with Instrument Uncertainty Models

(See A4 and A5 in Section 2.5.1)
Simulation of the selected measurement process in Step 11 is key to the successful implementation of the DfV guidelines. The simulation of the large volume measurement system reveals the areas of high uncertainty and enables the designer to make informed decisions on whether or not the process is capable. The majority of large volume aerospace assemblies are dimensionally inspected with the use of the laser tracker.

Wang et al. [51] produced the laser tracker position optimisation algorithm that uses a SoA uncertainty model for laser tracker measurement uncertainty to optimise laser tracker station positions whereby reducing the estimated uncertainty. Following the measurement instrument simulation and optimisation, if the process is not capable and does not satisfy the general rule of thumb that measurement uncertainty should equal to less than 10% of the tolerance band, then the design needs to be modified to accommodate the hardware limitations. This step is enhanced through optimisation of the measurement process (Step 13) if optimisation is possible. Optimisation of the measurement process can reduce the uncertainty and subsequently have an impact upon the answer to Decision B which is the primary reason for the optional parallel Step 13 within the framework. Optimisation of large volume measurement processes is critical when using instruments such as laser tracker because improper use, or ineffective use can cause the measurement uncertainty to be significantly increased as demonstrated in Chapter 3 and further discussed by Wang et al [51].

4.2.9.1. Decision A: Are All of the DfX Criteria Met?

Decision A is outside of the scope of DfV. It poses a question to the designer to ensure that the product has been designed for assembly, manufacturability and so on within the existing DfX toolbox. This question is revisited following the implementation of the DfV guidelines to prompt the designer to reconsider DfX so that the DfV process does not impose implications upon stakeholder requirements.

4.2.9.2. Decision B: Is the Process Capable?

In Decision B, the designer is asked if the measurement process is capable. The designer can then proceed onto Step 13 if the answer is yes. If the measurement process is incapable then the designer is directed to Decision C: This is a simple Yes/No response.

4.2.9.3. Decision C: Does a Suitable Instrument Exist?

In Decision C, the designer is asked to compare the results of the instrument selection and simulation with the data on available measurement instruments against the process and specification requirements specific to the product. The question asked if the designer has considered designing measurable features into the product itself (see Step 12C): This is a simple Yes/No response.

4.2.9.4. Decision D: What is the Limitation?

In Decision D, it is proposed that the significant limiting factors that prevent a product from being dimensionally inspected with confidence are due to the design specification, high levels of measurement uncertainty or an unmeasurable product. Data collated within the previous steps are used to determine the preferred route or consider alternative limiting factors as seen in Step 12A, 12B and 12C.

4.2.9.5. Decision E: Can the Metrology Process be Optimised?

In Decision E, the design is asked if the process is cost effective and the instrument uncertainty can be effectively reduced through knowledge based measurement planning. If yes, then the designer is directed to Step 13. Otherwise the designer is directed to Decision D: This is a simple Yes/No response.

4.2.10. Step 12A: Reduce Assembly Tolerances

(See A5 in Section 2.5.1)

In Step 12A, following the conventional DfX design process, if the assembly tolerances are within an interval that falls outside of an instrument's capability then the process or product needs to be modified within the early design stages. This is a key process within the DfV guidelines and it could result in significant cost savings further downstream. It has been observed through industrial collaborations that designs with unrealistic tolerances too often end up on the shop floor with the production staff having to work at the mercy of unachievable tolerances, which invariably leads to non-conformances and production delays. It is often undesirable to put in a change request for product redesign because the paper-work and process required within the aerospace industry for change request management to accommodate design modifications is hugely timely and costly, although, it has been shown to render favourable results when conducted effectively [102].

This step relates to Objective 3 in Section 1.4. The relationship between measurement plans, assembly analysis and tolerance allocation was defined within the MPM [96]. This step builds upon this work to include measurement uncertainty modelling through instrument and application specific simulation considering environmental and geometrical constraints, utilising tools such as the laser tracker position optimisation algorithm and the large volume metrology instrument selection database [51], [85], [103].

4.2.11. Step 12B: Redesign Assembly Tooling and or Process

(See A3 and A4 in Section 2.5.1)
The purpose of Step 12B is for the metrology community to feed requirements into the design of the assembly tooling and processes based upon individual or learned knowledge of the manufacturing environment and instrument capabilities. If the level of previously estimated measurement uncertainty exceeds requirements for dimensional inspection following the reduction of critical tolerances and metrology process optimisation and the tolerances cannot be further reduced due to specification constraints then the assembly process needs to be reconsidered. With all large volume metrology instruments, the larger the volume, the larger the uncertainty. The primary questions presented to the designer at this stage are:

a) Based on the measurement uncertainty analysis would the assembly process be better suited to a Type 1 or Type 2 approach (see Section 2.3.3)?
b) Can the assembly stages be divided into sub-assemblies to enable part-to-part assembly whereby containing the measurement uncertainty within smaller volumes?

This step relates to Objective 2 and Objective 6 in Section 1.4. Selecting an appropriate assembly strategy is not a simple problem. As Swift et al. [27] discussed, a well defined strategy can offer enormous benefits but there is a distinct lack of systematic approaches for defining an optimal assembly system. This step within the DfV framework guides the designer to consider geometric specification requirements against estimated measurement system uncertainty to aid in the decision process for selecting the most appropriate assembly system and sequence.

c) Can assembly jigs be reutilised through the assembly flow to reduce further variation from tooling alignment uncertainty and also reduce production costs?

Sub-assemblies are often introduced during the final assembly of large aerospace structures. Jig reduction can significantly reduce product variation through maintaining critical interfaces within a single setting [59]. As within part a) of Step 12B, the purpose of this question is to raise awareness of the potential increase in assembly variation by translating components between jigs and fixtures [104], [105]. The reduction in production costs through doing so is also of additional benefit.

4.2.12. Step 12C: Embed instrument specific measurement features

(See A1, A2, A5 in Section 2.5.1)
Step 12C builds upon the data collated during Steps 8 and 10. Following tolerance optimisation for measurability and assembly sequncing and process redesign, the questions posed are based around reducing measurement costs through simplification of the measurement task. There is currently a lack of available databases for instrument specific measurement features which has promoted projects to address this [101]. The primary question asked to the designer during this step is as follows:

a) What are the features proposed for measurement to verify the assembly against the specification and how can they be improved to enable improved measurement processes?

This step relates to Objective 1 and Objective 7 in Section 1.4. Measurement processes can be vastly simplified and optimised through feature-based design when considering the chosen metrology system for verification. Measurement systems can also be combined to reduce instrument specific limitations and define verification strategies based upon instrument specific capabilities [106]. Following the implementation of the DfV guidelines the designer is prompted to reconsider the design against the traditional design rules such that the benefits from optimised metrology processes can be weighed against the costs incurred from altering the manufacturing and assembly procedure.

4.2.13. Step 13: Optimise instrument plans and algorithms for process control and uncertainty reduction

(See A5 in Section 2.5.1)

Step 13 is arrived at through both Question B and Question E. Following a route of 'Yes' from Question B, has rendered a response that suggests the process is adequate for the product verification requirements, however, it is recognised that measurement process optimisation can lead to significant cost savings [51] where possible. Following a route of 'Yes' from Question E, has rendered a response that suggests the process is capable of being optimised to meet product requirements. Because of this, Step 13 is a critical step regardless of how it is reached, through Question B or Question E. The primary question asked to the designer during this step is as follows:

a) Can the measurement process/processes be optimised to reduce down-time, measurement uncertainty and cost?

Laser tracker processes can be optimised through novel methods as explored within the industrial case studies in Section 3.1.4. Metrology is often viewed as a non-value added process. Optimisation of a measurement plan to be carried out as an in-process activity can result in significant cost saving and cycle time reduction [75]. It can be seen in Figure 36 that an optional parallel task line is constructed between Step 11 and Step 13. This is used when the designer recognises that the design is at a mature enough stage to optimise the measurement plan and when there is an option to optimise the process. Use of measurement process optimisation software can also be used to drive the design of the assembly process to ensure adequate LOS is maintained to assist the design elements in Step 12.

Chapter 5

Implementation Strategy

In 2012, ADS embarked on a large scale development programme to redesign its flagship telecommunications platform, the Eurostar 3000. A collaboration between the University of Bath and ADS gave the author a unique opportunity to collaboratively apply the DfV guidelines to the Next Generation Mechanical Platform (NGMP) NEOSAT and work towards delivering an innovative solution to satellite structure assembly and verification, whereby optimising the design with the DfV guidelines during the early stage design phase. The purpose for redesigning the flagship telecommunications spacecraft was to raise market competitiveness through cost reduction, labour reduction, maximised product flexibility and improved process efficiency. For the author to effectively accomplish this task, the current manufacturing and assembly processes were base-lined capturing all of the previously mentioned criteria.

In order to introduce the DfV guidelines and test the proposed design process, a mock-up NEOSAT CAD model was created by ADS to baseline current features of the E3000 which was known to be consistent within the design of NEOSAT. The focus of the DfV implementation was on the NEOSAT service module as it contained all the critical geometrical features of the communications module.

Through the application of the DfV guidelines to the NEOSAT CAD mock-up, in collaboration with a multidisciplinary design team at ADS, the DfV guidelines were tested. Areas for opportunity within AIT for NEOSAT were highlighted which led to a physical demonstrator being constructed at the University of Bath to prove the results that were generated from the application of the DfV guidelines to the E3000. The next section discusses the challenges involved. This is followed by a discussion of defining the baseline process, i.e. the procedure that currently exists. This definition involves following the DfV process, but excluding any steps to improve the process at this stage.

5.1. Challenge

ADS is one of the leading spacecraft manufacturers in Europe. It is facing fierce competition from private organisations. The mechanical platform for the E3000 family of telecommunications satellites within ADS, is divided into two main structural components in order to optimise the industrial flow and build schedule. These two structural components are called the service module (SM) and communications module (CM). They are built separately in Stevenage, UK and brought together as part of the final integration stage in Toulouse, France.

ADS mechanical platform structures are currently built using conventional, monolithic assembly jigs and fixtures, which are bespoke for each stage of the build process and require significant time to set-up and align to meet the tight assembly tolerances. This process is costly and time consuming. Following final assembly and NDT, critical interfaces of the completed structures are also independently measured to verify their compliance to drawing, which is also a time consuming operation. The assembly jigs are significantly larger than the hardware they produce, covering large areas within the assembly clean rooms.

Within each assembly fixture, the key tooling interfaces are set to high degrees of precision using a laser tracker. The tooling interfaces are set and or verified prior to each spacecraft assembly and also at periodic intervals throughout the jig lifetime. The current structure build process also tends to be largely sequential with little parallel working, and where bonded joints are used, there are periods of non-productive time waiting for cures. The main challenge was to significantly reduce the cost and schedule of the mechanical assembly of satellite structures to improve competitiveness. The challenge posed by the author was to assess the DfV guidelines against the existing E3000 assembly process to understand if the following list could be improved with respect to time, cost and complexity reduction. The challenge undertook a combination of:

1. Understanding and managing build tolerances and requirements.

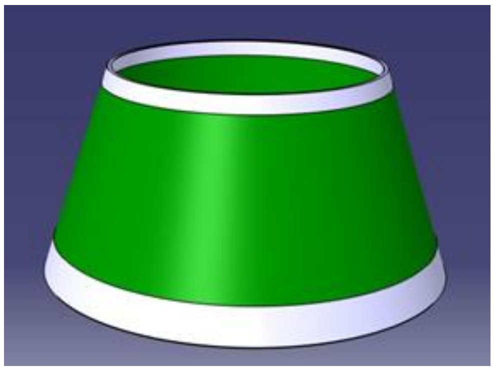
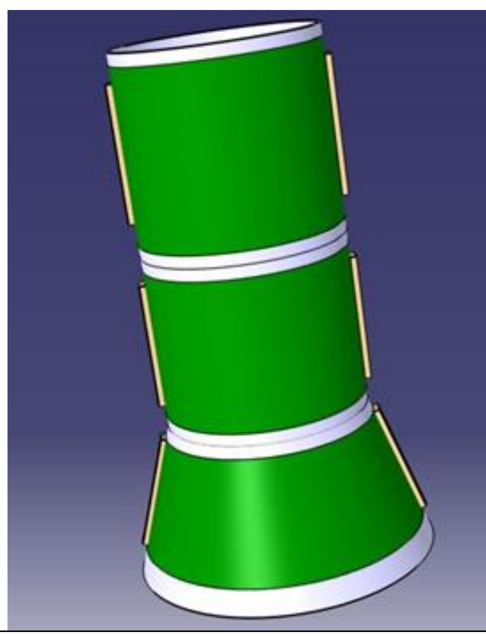
2. Modularity and assembly sequencing.
3. Use of ‘flexible’ tooling approaches.
4. Appropriate use of metrology to ‘assist’ assembly.
5. Automated verification approaches.

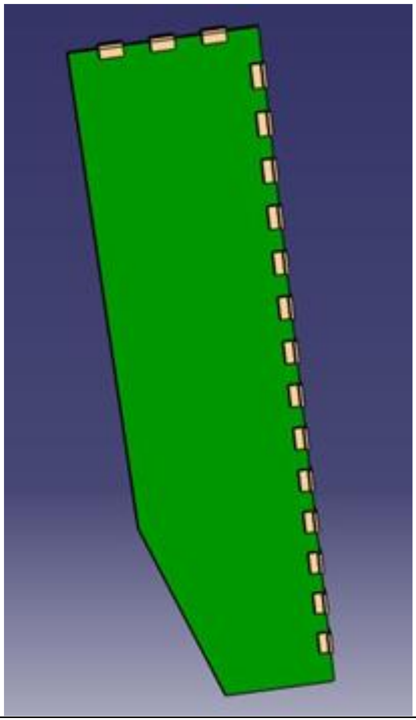
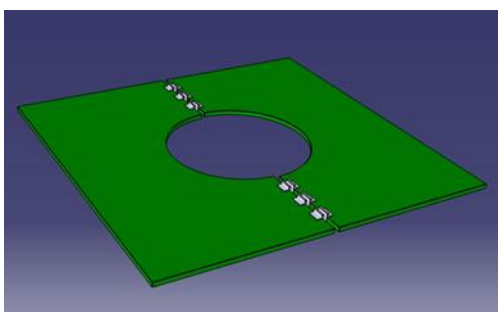
This study considered a wide range of possible tooling and metrology approaches and performed a holistic analysis to identify those most suited to mechanical platform assembly (in terms of technical capability and cost effectiveness). A physical demonstrator was designed and built for the purpose of trials to verify the selected technologies and approaches through application of the DfV framework.

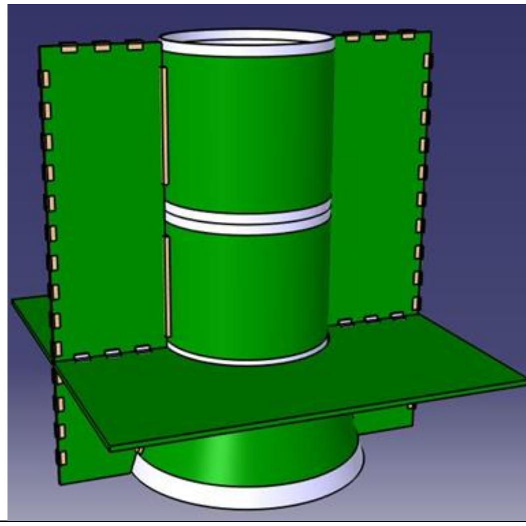
5.2. Baseline Process

The baseline process for the E3000 was documented as illustrated in the extract shown in Figure 37. The extended document was used to categorise the DfV framework requirements and hold the present status against the solution proposed post DfV implementation. Step 1 within the DfV framework requires an existing, preliminary CAD design. As part of the development programme. ADS worked with the author to design a baseline CAD model for the existing E3000. The baseline model extracted all key features that were to be congruent with the next generation NEOSAT design. Alongside the baseline CAD model, existing assembly and verification processes were mapped to capture the current E3000 status. The baseline was defined as using all current E3000 assembly techniques and technologies. The final output of the baseline exercise was an assessment summary that displayed the delta values, cost (£), tolerance band and elapsed time, illustrated in Figure 37, for comparison against each of the different build approaches derived from the DfV implementation. An overview of the baseline model with description can be found within Table 3.

Table 3: Baseline E3000/NEOSAT CAD model

Stage	Architecture	Assembly Notes
Stage 1		The SM cone is positioned within the launch vehicle attachment (LVA) base ring, which defines the base and a primary datum for the service module structure assembly. An upper ring is located and bonded onto the cone as an attachment site for the cylinder lower ring.
Stage 1a		SML1 Final Assembly Cone to cylinder jointing with bonded rings and T-cleats attached to cylinder and cone via bonding. All architecture accurately located prior to bonding with fixed jig positioning and setting with laser tracker. Cleat positional tolerance 0.2mm. Parallelism tolerance of upper and lower surface 0.1mm.

Stage 2a Stage 2b		Representing the lower shear walls, SM Y walls and X shear walls. Brackets are bonded onto the shear walls in bracket bonding fixtures as a sub-assembly before being attached onto the central cone-cylinder structure.
Stage 3a Stage 3b		Brackets are bonded onto the floors in bracket bonding fixtures as a sub-assembly before being attached onto the central cone-cylinder structure. All architecture accurately located prior to bonding with Fixed Jig positioning and setting/ verification with Laser Tracker

Stage 4		SML 2 and 3Assembly Floor and side panel attachment to Central Cone/Cylinder structure via Brackets and T-Cleats/Flexi-Cleats. All architecture accurately located prior to bonding with fixed jig positioning and verification with Laser Tracker

The baseline process was detailed within a value-stream map which was given the title of 'DfV Trade-off Database' for the purpose of comparing the before and after processes following the implementation of the DfV framework. The DfV trade-off database was used to assess the effectiveness of the proposed guidelines against cost, time and capability. The format of the tool was agreed with the stakeholders and consisted of four key elements of stakeholder interest to aid in mapping the existing processes:

1.) E3000 Tolerancing.
   a.) *Geometrical requirements and features.*
   b.) *Overall size of components.*

2.) E3000 Assembly Sequence.
   a.) *Critical interfaces at each assembly stage.*
   b.) *Labour required.*
   c.) *Elapsed time and cost.*

3.) E3000 SML1 and 2 Assembly Tooling.
   a.) *Cost of tooling.*

   b.) *Handling requirements.*
   c.) *Labour required.*
   d.) *Elapsed time and cost.*

4.) Metrology.
   a.) *Cost of metrology system.*
   b.) *Estimated in-process uncertainty per operation.*
   c.) *Labour required.*
   d.) *Elapsed time and cost.*

Each of the four areas were listed against the current assembly processes so that a cost matrix could be created at each stage. The overall cost was summarised on a separate spreadsheet with broken down timescales for each of the areas listed above to identify the areas of high cost and labour to reveal the bottlenecks within the existing processes. It was not essential for the DfV baseline to include all costs incurred during assembly and manufacture, only the key tooling and metrology times and costs were required. It is recognised that the competing DfX tools will consider other aspects of detail, such as DfM and DfA.

Current Service Module (SM): *Tooling & Metrology Trade-off Database*

Architecture	Size/Material	Assembly Notes	Tooling	Metrology	Verification	Time Scales	Jig £Cost	Additional Costs	£	Man Hours for Sub-Assy Process	Hrs	Jig / Metrology Cost broken down into Sub Assy Process Costs	£
SM Cylinder (SOL15) SM Cone (SOL16) Cylinder T-Cletas (SOL32 & 34) Cone T-Cleats (SOL30 & 31)	Cylinder ø 799.78mm Cylinder Length:1500mm Cone Large ø 1139.68mm Cone Height: 500mm Material: Aluminium	**SM Level 1 Assembly** Cone to Cylinder Jointing with Bonded Rings & T-cleats attached to Cylinder & Cone via Bonding All architecture accurately located prior to bonding with Fixed Jig positioning	SM Level 1 - G0076215 45µm	Leica AT-901B **£120k** 45µm	Leica AT-901B 45µm	Assembly Time 3 weeks*** (120Hr's) x 4 Technicians = Metrology Time 2 to 3 Days* Jig Setting (24Hr's) x 1 Operator Analysis/Verification Time 1/2 to 1 Day (8Hr's) x 1 Project Engineer	(£136k Jig DC's) (£50k Staging DC's) (+ £47k HR's****) (600hrs Jig Interface Cleaning, & Preparation 1 Day(8Hr's) x 1 Technician	Laser Tracker Annual Service/Calibration Cost: £6k Life: 1 year Cost Per Year = £6k Cost Per Spacecraft = £6k ÷ 6 = £1k Metrology Software Cost: £10k Life: 10 years Cost Per Year: £1k Cost Per Spacecraft = £1k ÷ 6 = £166	1000 167	Assembly Time Metrology Time Analysis/Verification Time Jig Maintenance/Prep Total Hours Total Cost (@ £52 per hour)	480 24 8 8 520 27040	Based on 6 spacecraft per year SM Level 1 - G0076215 - Cost = £233k SM Level 1 - G0076215 - Life = 10 years** Cost Per Year = £233k ÷ 10years = £23,300 per y Cost per Spacecraft = £23,300 ÷ 6 = £3883 Jig Cost for Sub Assy Process 1 Based on 6 spacecraft per year Leica AT901B Laser Tracker Cost = £120k Leica AT901B Laser Tracker Life = 50,000hrs (ap Cost Per Year = £120k ÷20 years = £6000 per ye Cost per Spacecraft = £6000 ÷ 6 = £1000 Metrology Cost for Sub Assy Process 1	3883 1000
SM Floor -X (SOL19)	Panel Thickness: 25mm LengthY: 1948mm Length X: 986.5mm Material: Aluminium Honeycomb/ Aluminium Skins	**SM Floor - Bonded Bracket Assembly** Brackets attached to panel via Bracket Bonding process All architecture accurately located prior to bonding with Fixed Jig positioning & setting/ verification with Laser Tracker. Jointing required (Joints not on Model) to attach SM Floor to Cylinder Drill on Assy.?	SM Floor - Bracket Bonding Jig - MT61911 45µm	Leica AT-901B **£120k** 45µm	Leica AT-901B 45µm	Assembly Time 1 Day Masking 1 Day Assembly & Tack-Bond 2 Days Masking & Pre-Inject 1 Day Inject 1 Day Grounding & NDT = 6 Metrology Time 1 Day Jig Setting (8Hr's) x 1 Operator Analysis/Verification Time 1/2 to 1 Day	**£20k £16k Jig DC's £4k Design & Procurement** Jig Interface Cleaning, & Preparation 1 Day(8Hr's) x 1 Technician	Laser Tracker Annual Service/Calibration Cost: £6k Life: 1 year Cost Per Year = £6k Cost Per Spacecraft = £6k Metrology Software Cost: £10k Life: 10 years Cost Per Year: £1k Cost Per Spacecraft = £1k	1000 167	Assembly Time Metrology Time Analysis/Verification Time Jig Maintenance/Prep Total Hours Total Cost (@ £52 per hour)	96 8 8 8 120 6240	Based on 6 spacecraft per year SM Floor Bracket Bonding Jig MT61911 - Cost = SM Floor Bracket Bonding Jig MT61911 - Life = Cost Per Year = £20k ÷ 10years = £2000 per year Cost per Spacecraft = £2000 ÷ 6 = £333 Jig Cost for Sub Assy Process 2a Based on 6 spacecraft per year Leica AT901B Laser Tracker Cost = £120k Leica AT901B Laser Tracker Life = 50,000hrs (ap Cost Per Year = £120k ÷20 years = £6000 per ye Cost per Spacecraft = £6000 ÷ 6 = £1000 Metrology Cost for Sub Assy Process 2a	333 1000
SM Floor +X (SOL18)	Panel Thickness: 25mm LengthY: 1948mm Length X: 986.5mm Material: Aluminium Honeycomb/ Aluminium Skins	**SM Floor - Bonded Bracket Assembly** Brackets attached to panel via Bracket Bonding process All architecture accurately located prior to bonding with Fixed Jig positioning & setting/ verification with Laser Tracker Jointing required (Joints not on Model) to attach SM Floor to Cylinder & SM Floor to Vertical Shearwall Panels Brackets/Drill on Assy.?	SM Floor - Bracket Bonding Jig - MT61911 45µm	Leica AT-901B **£120k** 45µm	Leica AT-901B 45µm	Assembly Time 1 Day Masking 1 Day Assembly & Tack-Bond 2 Days Masking & Pre-Inject 1 Day Inject 1 Day Grounding & NDT = 6 Days (48 Hr's) Metrology Time 1 Day Jig Setting (8Hr's) x 1 Analysis/Verification Time 1/2 to 1 Day	Jig Costs **£20k £16k Jig DC's £4k Design & Procurement** Jig Interface Cleaning, & Preparation 1 Day(8Hr's) x 1 Technician	Laser Tracker Annual Service/Calibration Cost: £6k Life: 1 year Cost Per Year = £6k Cost Per Spacecraft = £6k ÷ 6 = £1k Metrology Software Cost: £10k Life: 10 years Cost Per Year: £1k Cost Per Spacecraft = £1k	1000 167	Assembly Time Metrology Time Analysis/Verification Time Jig Maintenance/Prep Total Hours Total Cost (@ £52 per hour)	96 8 8 8 120 6240	Based on 6 spacecraft per year SM Floor Bracket Bonding Jig MT61911 - Cost = SM Floor Bracket Bonding Jig MT61911 - Life = Cost Per Year = £20k ÷ 10years = £2000 per year Cost per Spacecraft = £2000 ÷ 6 = £333 Jig Cost for Sub Assy Process 2b Based on 6 spacecraft per year Leica AT901B Laser Tracker Cost = £120k Leica AT901B Laser Tracker Life = 50,000hrs (ap Cost Per Year = £120k ÷20 years = £6000 per ye Cost per Spacecraft = £6000 ÷ 6 = £1000 Metrology Cost for Sub Assy Process 2b	333 1000

Figure 37: For illustration purposes only. Extract from DfV trade-off database – baseline assembly and verification process.

5.2.1. Current Status

The relevant information required to assess the current baseline status against the proposed DfV framework resultant is detailed in the following section. DfV Steps 1 to 6 are associated with the fundamental design and are not inherently covered by the DfV framework. The following steps are applied against the existing process to capture the current status and reapplied against the NEOSAT mock-up model in the following chapter to test the DfV framework guidelines.

5.2.1.1. Step 7 Baseline: Define Product Verification Requirements and Stages

(See A2 and A5 in Section 2.5.1)

The SM-CM interfaces have been documented in Table 4.

Table 4: For illustration purposes to show the reader the level of detail required to follow Step 7. Key Assembly Interface features.

	Interfaces			*Attachment method*	*Interface Type*
Internal SM Interfaces	SM Floor	to	X Shearwall	Bonded brackets	Friction
	SM Floor	to	Lower X wall	Bonded brackets	Friction
	SM Floor	to	Lower Y wall	Bonded brackets	Friction
	SM Floor	to	Cone/Cylinder ring	Bolted directly to ring	Close Tol
	X Shearwall	to	Lower X wall	Bonded brackets	Friction
	X Shearwall	to	Cone/Cyl T-Cleats	Bonded brackets	Friction
	X Shearwall	to	LVA ring	Bolted brackets	Close Tol
	X Shearwall	to	Cylinder rings	Bonded brackets	Friction
	X Shearwall	to	Battery	Bolted brackets	Close Tol
	X Shearwall	to	-Z Closure panel	Bolted cleats	Close Tol / Friction
	Lower Y Shearwall	to	SM Floor	Bonded brackets	Friction
	Lower Y Shearwall	to	Lower Y wall	Bonded brackets	Friction
	Lower Y Shearwall	to	Cone/Cyl T-Cleats	Bonded brackets	Friction
	Lower Y Shearwall	to	LVA ring	Bolted brackets	Close Tol
	Lower Y Shearwall	to	-Z Closure panel	Bolted cleats	Close Tol / Friction
	Lower Y wall	to	Lower X wall	Bolted cleats	Close Tol / Close
	Lower Y wall	to	-Z Closure panel	Bolted cleats	Close Tol / Friction
	Lower X wall	to	Battery	Edge inserts	Open Tol
	-Z Closure panel	to	LVA ring	Bonded brackets	Friction
	Battery supp't gusset	to	Lower X wall	Bonded brackets	Friction
	Fixed upper X panels	to	SM Floor	Bonded Brackets	Friction
	Fixed upper X panels	to	X Shearwall	Bonded Brackets	Friction
CM to SM Interfaces					
	Main Y shearwall	to	SM Floor	Bonded brackets	Friction
	Main Y shearwall	to	SM Cyl T-Cleats	Bonded brackets	Friction
	CM Floor	to	SM X shearwall	Bonded brackets	Friction
	SM Floor	to	Y wall	Bonded bracket	Friction
	SM Floor	to	X Closure panel	Bonded brackets	Friction

The critical stages for verification were identified on a process map to illustrate the key features that require inspection as seen in Figure 38. The red box represents the global assembly datum whilst the green boxes represent components with critical features that require verification for latter stage assembly processes.

The verification requirements for the SML1, 2 and 3 assembly stages are specified to ensure a successful SM-CM mate which is what drives the current tolerances. The SM and CM are brought together as two complete sub-assemblies and cannot be altered within the final assembly line. The current methods to promote RFT assembly of major E3000 substructures which have not had prior trial assembly and to avoid fouls or induction of assembly stresses, an overall flatness tolerance of ±0.05mm is specified along E3000 panel interfaces up to 4m long. Assembly jigs are currently measured, reworked and re-measured to meet this requirement. It takes 40 hours to align a build jig with 20 interfaces – an average of 2 hours per interface. Table 5 shows the measured data for a SM Y shear wall jig. The total length of the jig is approximately 4.5m, and each set of bonded brackets along an edge of the panel has a total flatness / positional tolerance requirement of 0.05mm.

Table 5: Historic laser tracker measurement data for the E3000 SM Y Shear Wall assembly jig.

Year	Total number of measurements	Total meeting the requirement	Percentage %
2011	59	49	83
2010	126	99	79
2009	84	52	62

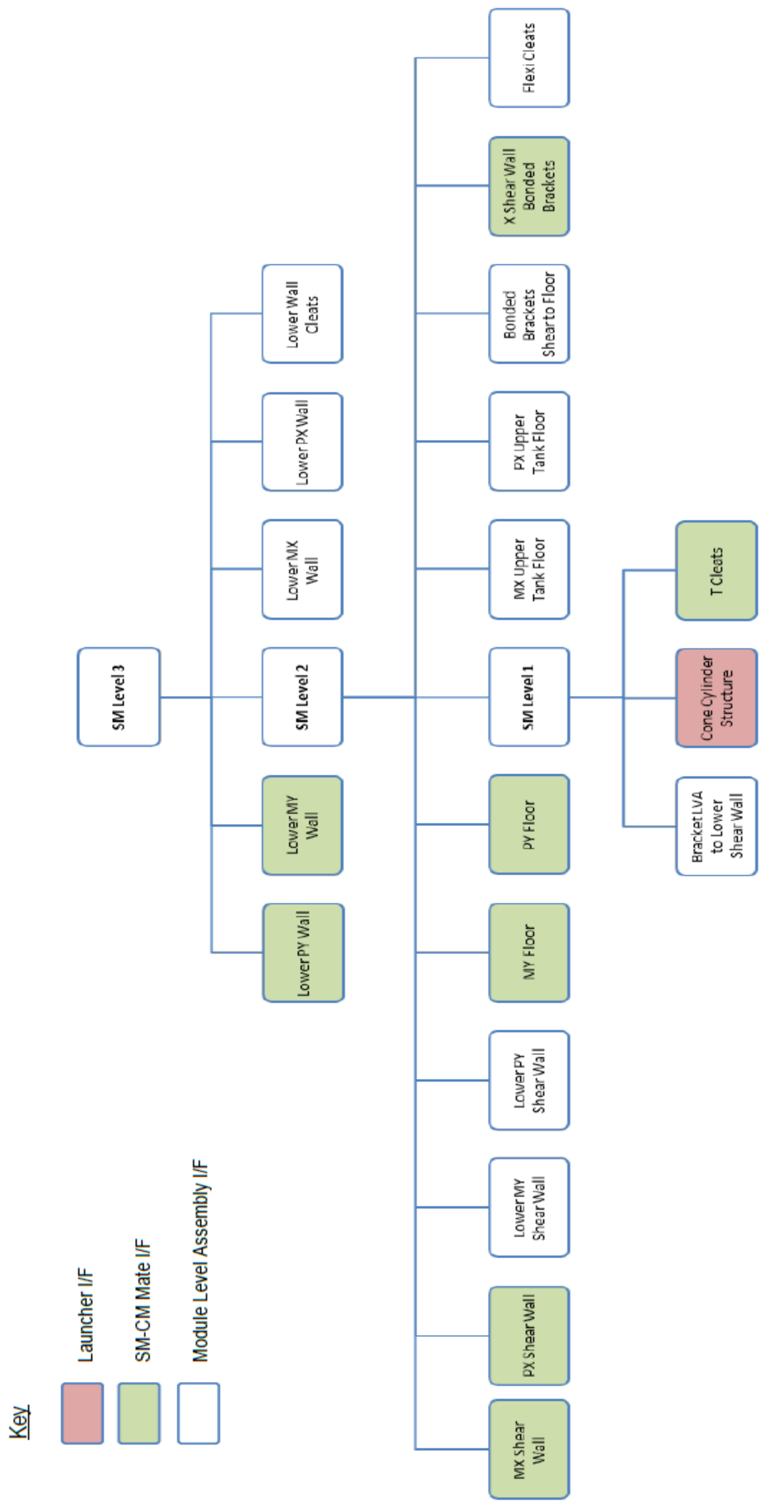


Figure 38: Service module key features for inspection during assembly stages.

These measurements are taken prior to each project build, with an average of 10 builds per year. The table shows that there are significant occurrences where the jig is not within design specification. Over time a jig moves or deforms. When this happens the jig is reconfigured to meet requirements. From Table 5, the average number of interfaces that are not within specification is approximately 25%. Re-setting a jig takes approximately 0.5 man days per interface (4 hours); this includes the measurement time of 2 hours. This value may be optimistic for the more complex and larger build jigs such as the SML1, SML2/3 and CML2 jigs.

Compared to assembly stages, later in the structure build sequence, the cone-cylinder build tolerances are relatively relaxed when compared with other local tolerances. The total height of the assembly defines the datum for the SM - CM mate, so it follows that every other interface is referenced to this plane. Therefore, if the other interfaces are accurately controlled relative to this plane, some degree of flexibility can be allowed in this build. In total there are 16 interfaces with the hardware.

The bonded bracket jigs have a generic total flatness / positional tolerance of ±0.05mm over each interface up to 3m long. Panels tend to have an interface along the entire length of each of its four edges. Generally there are 8 tooling interfaces to each panel, two per panel edge.

The tolerances on SML2/3 build stages are tighter than that of the Cone Cylinder assembly (SML1). The majority of critical interfaces have a total flatness / positional tolerance of ±0.05mm. The SM assembly jigs are shown in Figure 39 and Figure 40, which are typical of all SM and CM build jigs in terms of size and complexity. The SML2 / 3 build jig has 40 interfaces to the structure. As this jig accounts for 2 builds, it can be assumed that as with the SML1 jig there are 20 structure interfaces per build. It is assumed for the purposes of this thesis that as they are similar in complexity, the CM jigs, although not covered explicitly covered, also have approximately 20 interfaces with the structure per build stage.

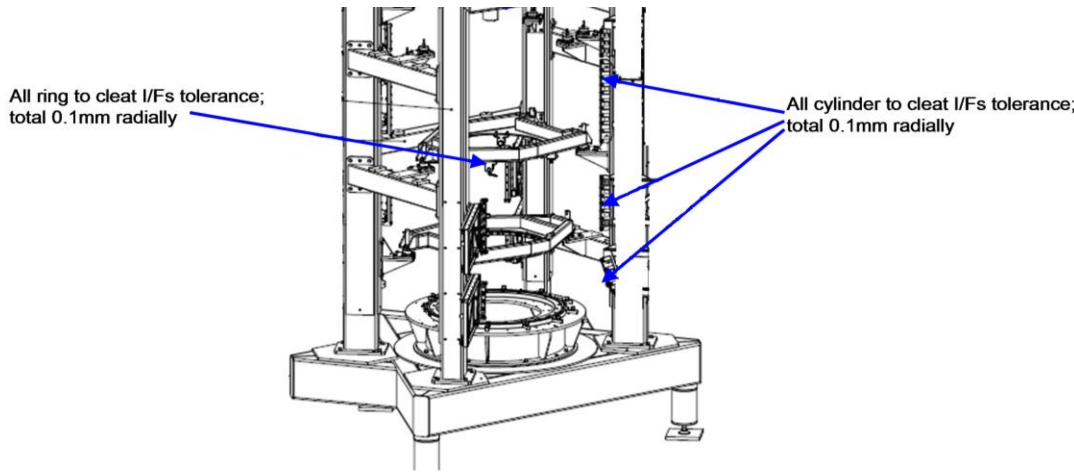


Figure 39: Extract of SML1 assembly jig.

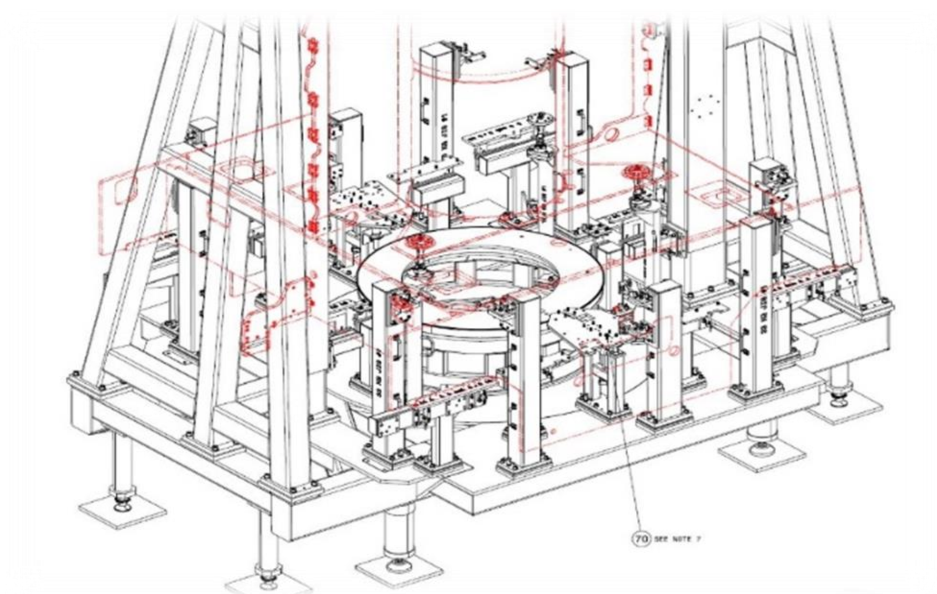


Figure 40: Extract from current E3000 SML2/3 assembly jig showing complexity of tooling design, setting and verification requirements.

5.2.1.2. Step 8 Baseline: Detail Product Specification and Assembly Process against Verification Requirements

(See A2, A4 and A5 in Section 2.5.1)

The product verification requirements have been visually represented to highlight the critical interfaces and tolerance requirements (Figure 41, Figure 42). In accordance with Figure 38, areas marked 0 to 3 are verified during SML1 build and areas marked 4 to 5 are verified during SML2 and 3 build. The verification requirements are currently inspected with a laser tracker. The laser tracker is used for both jig setting, commissioning, recertification and product verification.

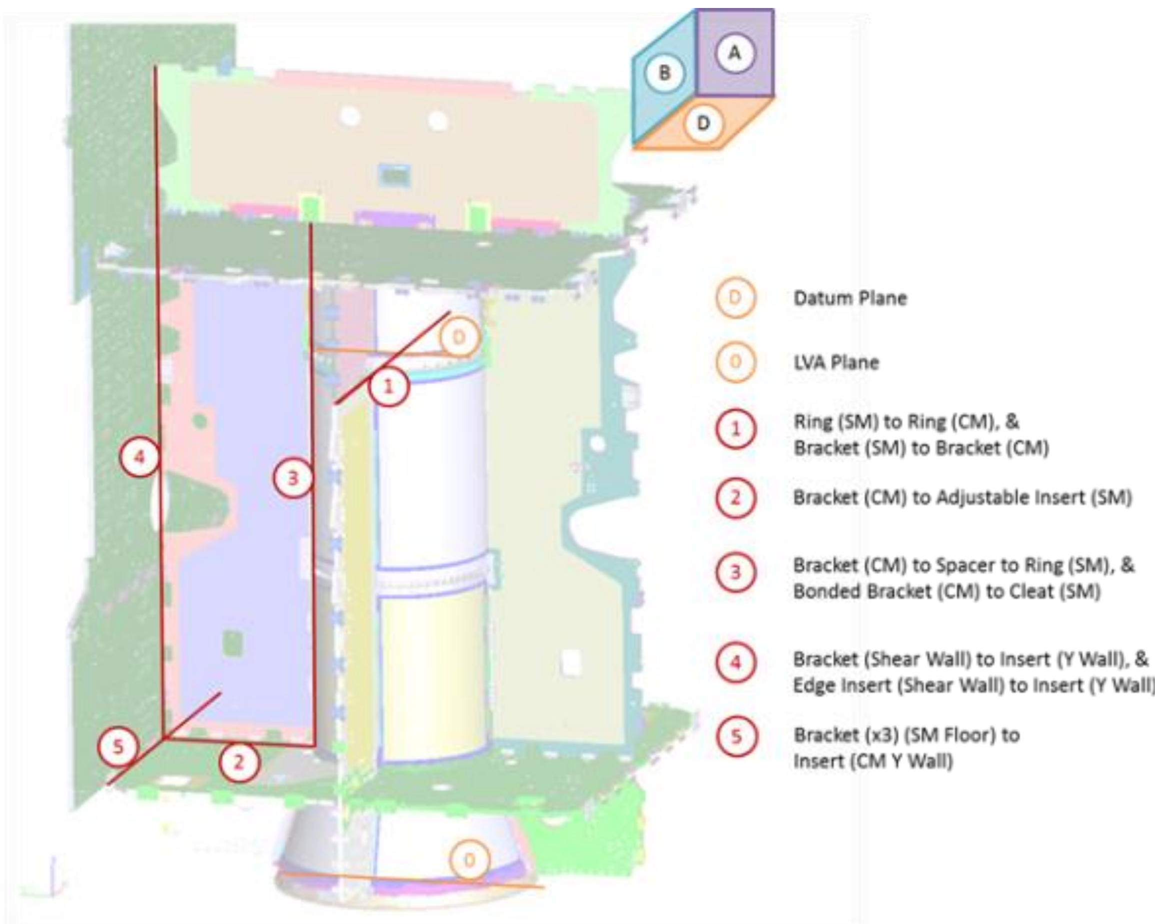


Figure 41: SM critical assembly interfaces.

A section of the CM can be seen in Figure 41 to illustrate the features that are critical for the SM-CM mate following the equipping stage.

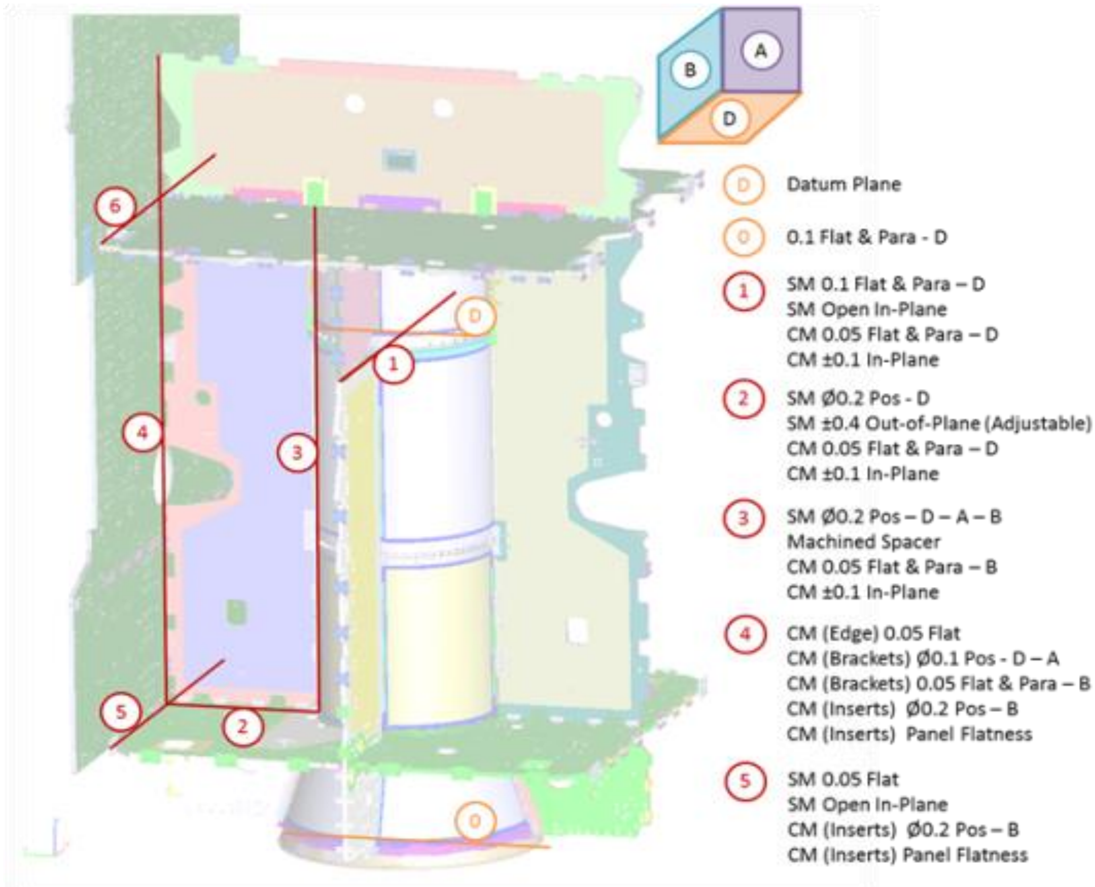


Figure 42: SM critical assembly interfaces and verification requirements.

5.2.1.3. Step 9 Baseline: Establish Factory Scale, Environmental Conditions and Constraints

(See A2 and A5 in Section 2.5.1)

A scale mock-up of the assembly room was drawn with existing jig locations to define the constraints placed upon the metrology instruments for inspection planning as shown in Figure 43. Limited space can lead to limited line of sight and poor measurement conditions. To fully optimise the metrology process for measurement planning and assembly sequencing, the shop floor layout forms a fundamental deliverable. Environmental data were captured to quantify the thermal variance throughout the day as thermal gradients cause significant variance within structural dimensions and are one of the primary sources for assembly variation uncertainty.

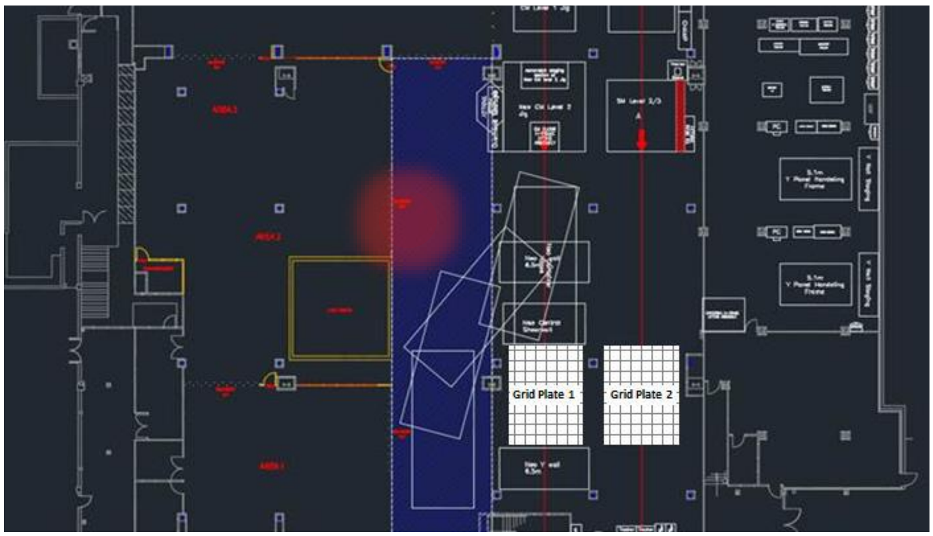


Figure 43: For illustration purposes only. Andromeda assembly room within ADS Stevenage.

5.2.1.4. Step 10 Baseline: Process Specific Instrument Selection

(See A1, A2, A5 in Section 2.5.1)

As the metrology processes for the existing build approaches have been established – this step is redundant within the base-lining exercise. The type of instrument used was documented and represented within the DfV trade-off database as shown in Figure 37

5.2.1.5. Step 11 Baseline: Simulate Verification Processes with Instrument Uncertainty Models

(See A4 and A5 in Section 2.5.1)

ADS assemble the E3000 service module in a series of levels. Level one consists of the assembly of the service module cone, cylinders, rings and T-cleats and is completed within the Service Module Level 1 (SML1) jig. The SML1 jig, as illustrated in Figure 44, was fitted with 31 reference network drift nests that were bonded onto the steel frame in various locations to maximise laser tracker LOS.

To quantify the estimated measurement uncertainty for laser tracker alignment within the current SML1 build stage, the existing operator measurement stations were recorded and inserted into the NPL laser tracker simulator [61].

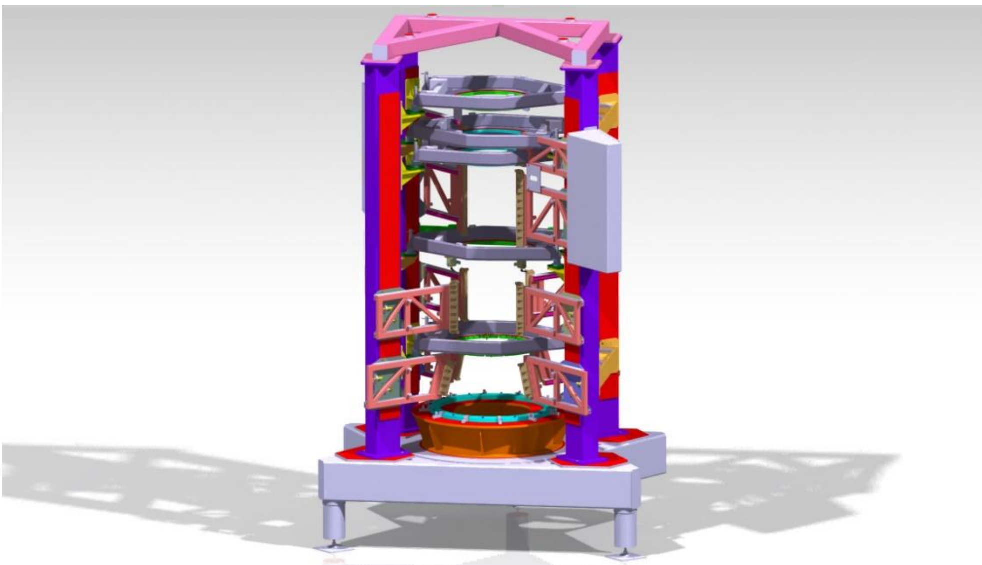


Figure 44: E3000 SML1 assembly jig.

Each of the ring cradle pick-ups was set with the laser tracker to a design and flatness parallelism tolerance of 0.1mm as seen in Figure 45. To adequately measure the SML1 jig within the bounds of this tolerance with confidence, the metrologist must ensure that the accumulation of uncertainties does not exceed an excessive amount such that the uncertainty bounds run outside of the tolerance limits as detailed within Figure 13. Through use of the NPL laser tracker model for determining in-process measurement uncertainty, the drift nest reference network uncertainty can be assessed based upon known measurement locations. Following the assessment of the existing reference network measurement uncertainty, the laser tracker measurement station positions can be optimised to reduce the accumulated measurement uncertainty [51]. The laser tracker position optimisation algorithm was run using the SML1 jig CAD and X, Y, Z reference network coordinates. The results revealed that through the optimisation of the laser tracker positions, the uncertainty surrounding the measurements of the reference network points could be reduced by 80%. The original uncertainty magnitude root mean square (RMS) for all 31 points was 0.1mm, following optimisation this was reduced to 0.02mm.

The line of sight was checked using the nominal SML1 CAD model and the laser tracker positions were optimised based upon reducing the in-process measurement uncertainty. The CPU time took approximately twenty minutes for the simulation to complete, the resultant laser tracker positions are graphically illustrated within Figure 47.

A typical rule of thumb within metrology is that the measurement uncertainty should not exceed more than 10% of the tolerance band. This is due to the reduction in available tolerance allocation for measurement. After SoA optimisation, the laser tracker measurements of the reference network points gave an uncertainty that already breaks this rule. There are few 3D coordinate measurement instruments that can cost effectively measure with a high degree of confidence when assessing geometries with tolerances of 0.1mm parallelism over $3m^3$ volume. The results from the uncertainty analysis show that although the process can be significantly optimised, the tolerances set within the design stage are not achievable through current practices.

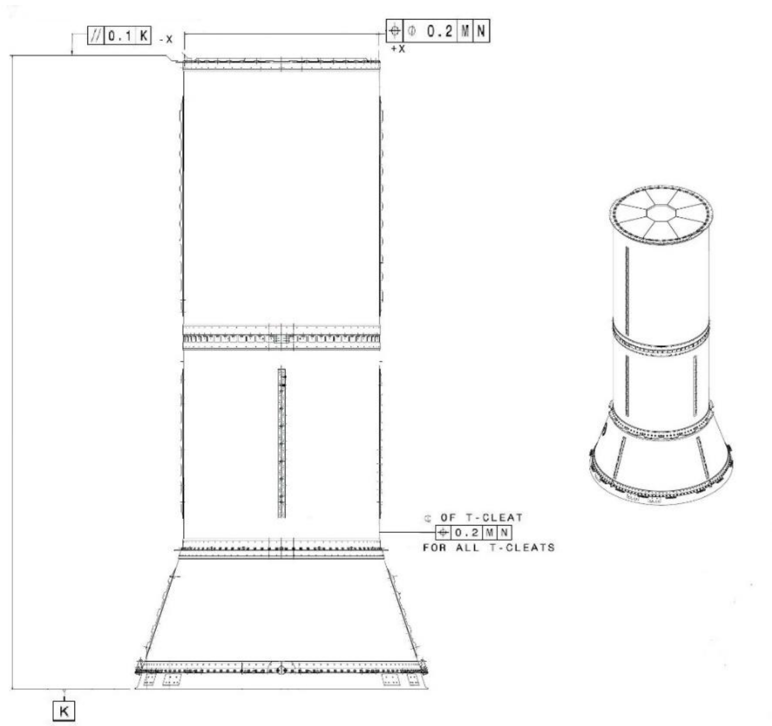


Figure 45: E3000 SML1 cone and cylinder assembly.

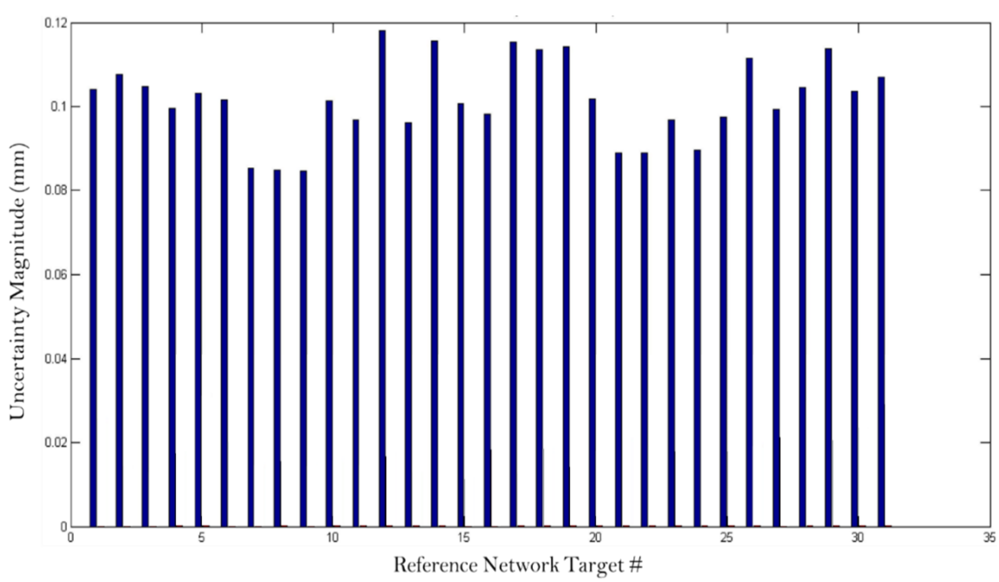


Figure 46: SML1 jig reference network estimated laser tracker measurement uncertainty.

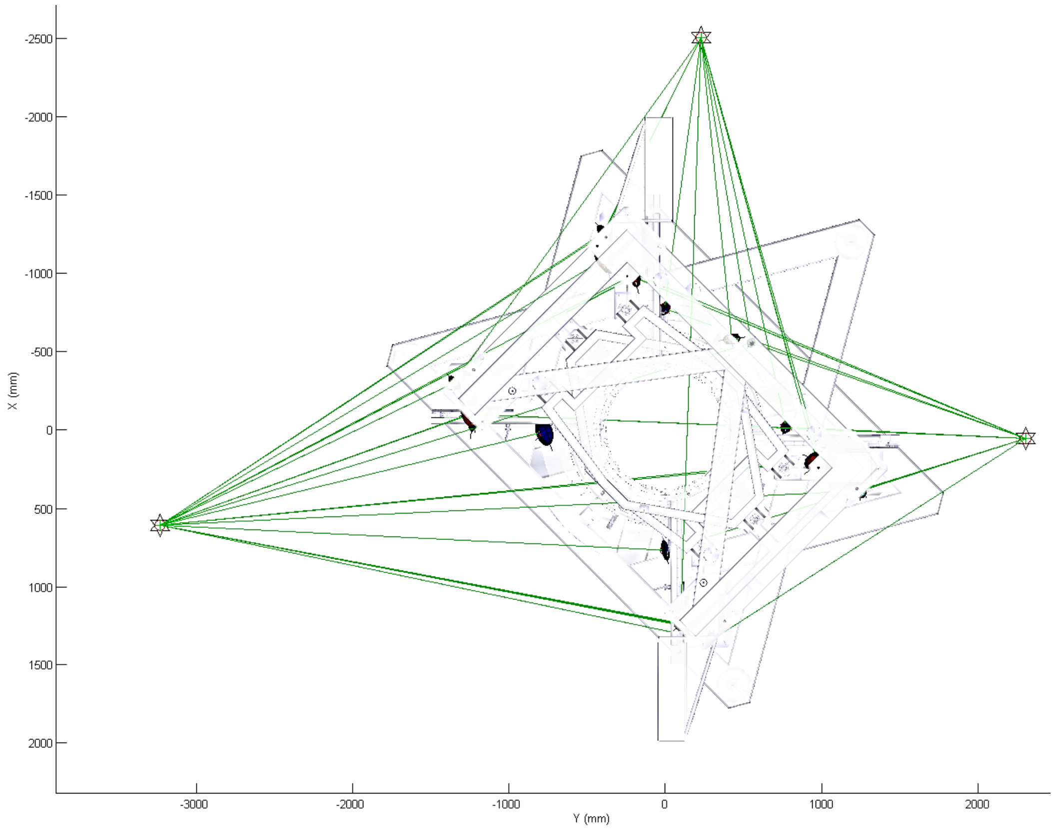


Figure 47: The red stars represent the laser tracker positions for estimating in-process measurement uncertainty replicating the existing process. The green lines represent the line of sign from the laser trackers to each measured target.

5.2.1.6. Steps 12A, B, C Baseline: Reduce Assembly Tolerances, Redesign Assembly Tooling and or Process, Embed Instrument Specific Measurement Features

(See A1, A2, A3, A4 and A5 in Section 2.5.1)

Steps 12A to C with the DfV framework are for the purpose of optimising the product design for verification during early design stages. The baseline process that captures the existing assembly process for the E3000 does not therefore require this step.

To baseline the uncertainty of the current build process for comparison against the DfV rendered designs, the GUM approach (See 3.1.1) was applied to the existing E3000 assembly methods as detailed in Table 6, Table 7 and Table 8.

Table 6: Table of assumptions for current E3000 uncertainty during build calculations [45], [57], [108], [111].

Assumptions		
Parameter	**Value**	**Units**
Temperature Variation during setting	1.50	°C
Temperature Variation during build	3.00	°C
Assembly Jig Height	5.00	m
Laser Tracker Distance	5.00	m
Laser Tracker Base Uncertainty	15.00	µm
Laser Tracker Uncertainty	6.00	µm/m
Steel CTE	12.00	µm/m/°C
CFRP CTE	6.00	µm/m/°C
Aluminium CTE	24.00	µm/m/°C
Photogrammetry Base Uncertainty	10.00	µm
Photogrammetry Uncertainty/m	10.00	µm/m
Thermal Scaling	90.00	%
Main Assembly Height	3.00	m

Table 7: Uncertainty analysis of tool setting. The laser tracker measurement distance was based on existing processes where it has to be offset from the fixture due to surrounding staging.

Main Assembly Fixture Setting				
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertainty**
Laser Tracker Alignment	100.00	Normal	2.00	50.00 µm
Laser Tracker	45.00	Normal	2.00	22.50 µm
SMR Centering	6.00	Normal	2.00	3.00 µm
Drift Nest Centering	6.00	Normal	2.00	3.00 µm
Tool Setting Tolerance	50.00	Rectangular	1.73	28.87 µm
Thermal Expansion	90.00	Normal	2.00	45.00 µm
			Standard Uncertainty	76.70 µm
			Expanded Uncertainty (k=2)	153.40 µm

Table 8: Uncertainty analysis of structural build. During the structural assembly of the E3000 within the MAF, the thermal CTE differences between the steel fixture and the carbon fibre structure presents a large uncertainty. The thermal variations can be up to 3℃ during structure build. The different between steel and carbon fibre ***x*** *jig height* ***x*** *temperature variation = thermal expansion disparity.*

Main Assembly Fixture Build Variation

Uncertainty Component	Value	Distribution	Divisor	Standard Uncertainty	
Fixture Setting Uncertainty	153.40	Normal	2.00	76.70	µm
Thermal Expansion Disparity	90.00	Normal	2.00	45.00	µm
			Standard Uncertainty	88.92	µm
			Expanded Uncertainty (k=2)	**177.85**	µm

The overall estimated assembly uncertainty is approximately ±0.18mm within two standard deviations. The current estimation of assembly variation through the GUM analysis (see Section 3.1.1) of the E3000 assembly method exceeds the existing tolerance limits of ±0.05mm.

5.2.1.7. Step 13: Optimise Instrument Plans and Algorithms for Process Control and Uncertainty Reduction

Similar to Step 10, Step 13 is redundant within the base-lining stage as it is solely a part of the optimisation process.

Chapter 6

Using DfV to Improve the Process

The previous chapter identifies the baseline process for the current E3000 construction. This chapter applies the DfV guidelines to make improvements upon the baseline process.

6.1. Step 7 (DfV): Define Product Verification Requirements and Stages

(See A2 and A5 in Section 2.5.1)

The DfV framework Step 7 requires the designer to identify all critical assembly features and stages at which the features require verification prior to follow on assembly processes. The baseline process for current verification requirements, detailed in Table 4, show that the key assembly features that require verification during the SML1 and 2 build processes are the external brackets and rings that interface with the CM.

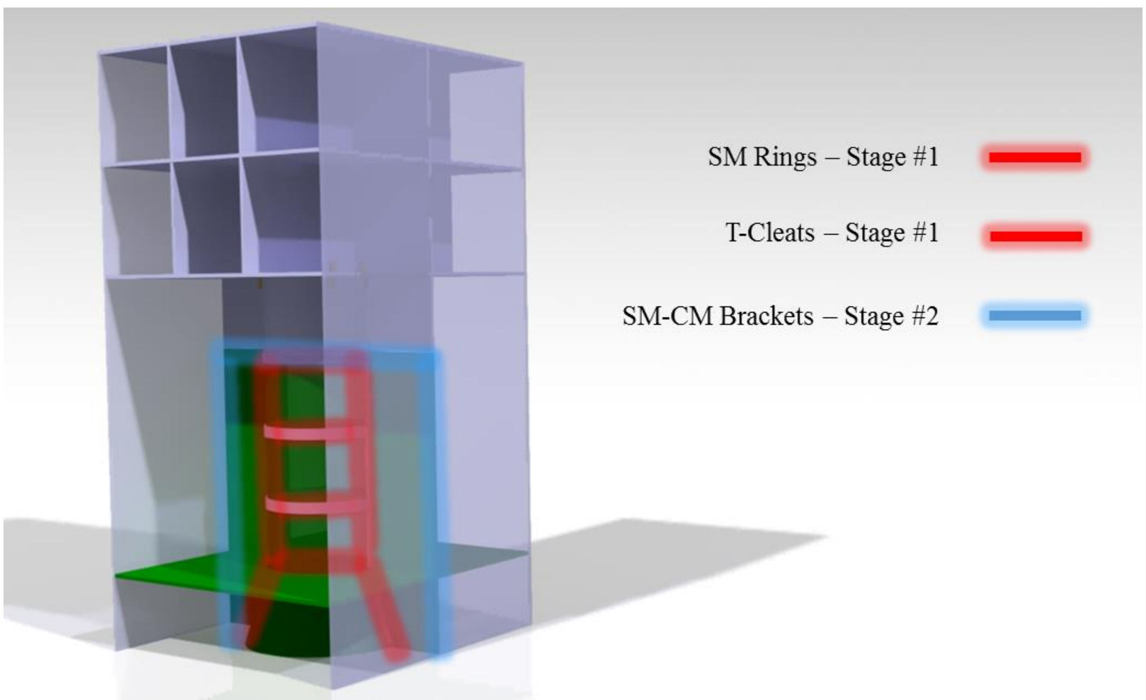


Figure 48: SML1 and 2 critical verification features and stages.

6.2. Step 8 (DfV): Detail Product Specification and Assembly Process against Verification Requirements

(See A2, A4 and A5 in Section 2.5.1)
Allocating similar tolerances to the E3000/NEOSAT mock-up CAD model, the following specification can be applied as seen in Figure 49.

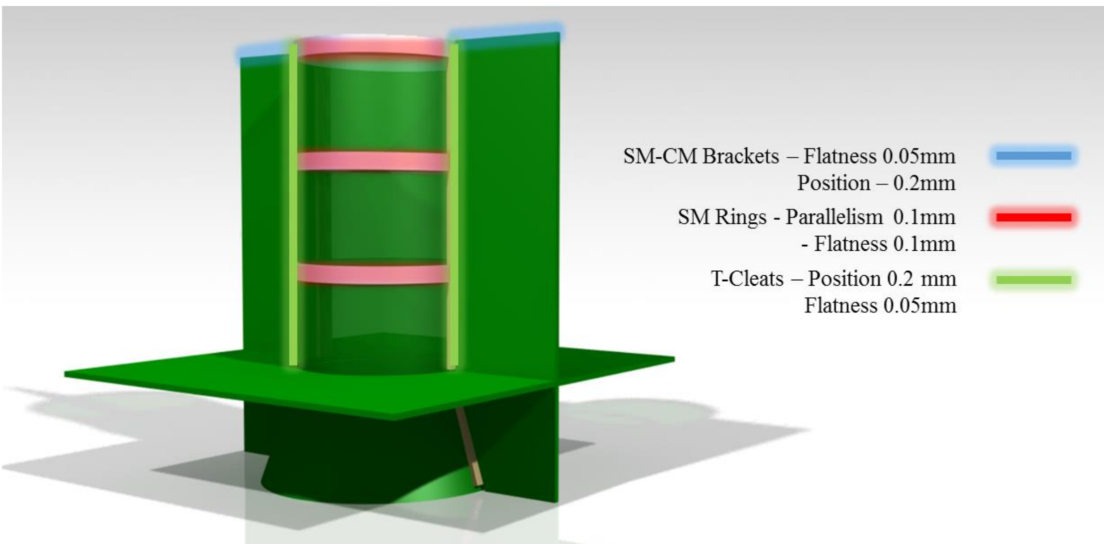


Figure 49: E3000/NEOSAT mock-up assembly critical features and tolerances.

Prior to assembly of Levels 1 and 2 (see Figure 38), the assembly jigs require dimensional verification, following assembly the spacecraft structure is measured directly and is transported to NDT. Post NDT, the product is measured directly. If the product passes the dimensional checks then it is translated into the SML2 jig. Prior to the craft being located within the SML2 jig, the jig has undergone a dimensional survey with a laser tracker. The follow on assembly stages are taken as detailed in Figure 38. Following further NDT checks, the product is measured with respect to the assembly jig which acts as a go/no-go gauge. The measurement requirements are further detailed in Table 9.

Table 9: Dimensional verification stages against build flow.

Dimensional Verification Requirements and Assembly Stage					
Step	**Process**	**Stage**	**Measurand**	**Jig**	**Spacecraft**
1	SML1 Jig Certification	1	Tooling pick-ups for all interfaces	40 hours	
2	Product Assembly	1			
3	Measure assembly	1	T-cleat positions and upper ring		16 hours
4	NDT	1			
5	Post-NDT	1	T-cleat positions and SM rings		16 hours
6	SML2 jig Certification	2	Tooling pick-ups for all interfaces	40 hours	
7	Product Assembly	2			
8	Remove product from Jig	2			
9	NDT	2			
10	Post -NDT	2			
11	SML2 Jig Recertification	2	SM-CM brackets and SM rings	40 hours	
Total Measurement Time for Stages 1 and 2 =					152 hours

6.3. Step 9 (DfV): Establish Factory Scale, Environmental Conditions and Constraints

(See A2 and A5 in Section 2.5.1)

The factory scale and environmental conditions are unchanged from the baseline. It was noted through running this exercise that there were fan heaters directly above one of the final assembly jigs as illustrated in Figure 50. Learning from individual knowledge it became clear that the fan heaters had a significant impact upon the assembly variation and in turn caused production delays. The fan heaters were automatically controlled by a central system and could not be turned off by the shop floor staff. Air flow and thermal gradients have a significant impact, not only on metallic structures, but also laser tracker measurements [107]. Throughout the course of a single day, the jig showed thermal fluctuations of over 3℃ across a single 5m vertical support beam. The CTE of steel is approximately 0.012mm/m/℃ [108]. The thermal instability due to the fan heaters revealed an estimated uncertainty of $\pm$0.18mm which far exceeds the $\pm$0.05mm tolerance across the upper brackets. The other constraint noted within the assembly room was the use of the shutter doors. Laser tracker measurements could not be acquired when the doors were open. It was observed that this often created delays to production when the doors were used on an irregular basis.

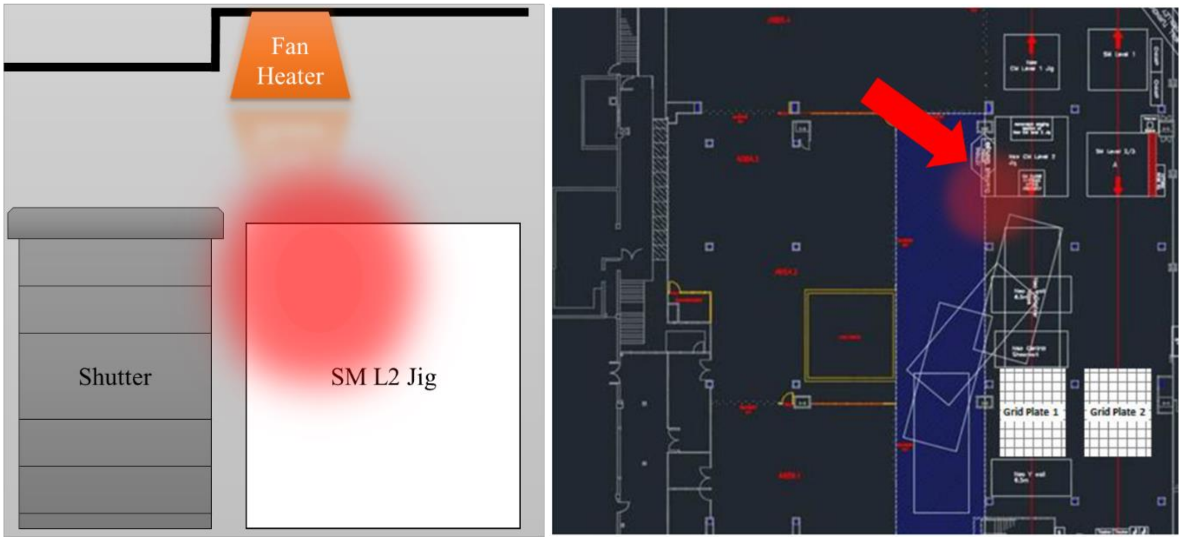


Figure 50: Thermal variation introduced through fan heaters blowing on a single side of assembly jig.

6.4. Step 10 (DfV): Process Specific Instrument Selection

(See A1, A2, A5 in Section 2.5.1)

Having assessed the specification requirements against measurement volumes and inspection stages, the next stage was to undertake the instrument selection. To aid in the selection process, the data collated during the previous DfV steps were entered into the DfV trade-off database (see Table 11) created for the DfV implementation. The scale and tolerance requirements for the E3000/NEOSAT CAD model restrict the available metrology instruments to laser trackers, photogrammetry systems and CMMs. The current measurement times for the assembly jigs and spacecraft, listed in Table 9, highlight the cost incurred in metrology processes due to the high level of man hours required for the existing tasks. Photogrammetry, as discussed in the third case study and shown to have similar uncertainty levels to the laser tracker, revealed the potential for rapid recertification although requires a degree of consideration within the design phase to enable effective implementation.

Table 10: Metrology instrument selection based upon measurement and specification requirements.

Dimensional Verification Requirements and Assembly Stage								
Step	**Process**	**Stage**	**Measurand**	**Jig (Current)**	**Spacecraft (Current)**	**Measurement Volume**	**Tightest Tolerance**	**Capable Measurement Instrument**
1	SML1 Jig Certification	1	Tooling pick-ups for all interfaces	40 hours		5m x 5m	0.05mm	Laser tracker
2	SML1 Jig Re-Certification		Tooling pick-ups for all interfaces	40 hours		5m x 5m	0.05mm	Laser Tracker Photogrammetry CMM
3	Product Assembly	1						
4	Measure assembly	1	T-cleat positions and upper ring		16 hours	3m x 3m	0.05mm	Laser Tracker Photogrammetry CMM
5	NDT	1						
6	Post-NDT	1	T-cleat positions and SM rings		16 hours	3m x 3m	0.05mm	Laser Tracker Photogrammetry CMM
7	SML2 jig Certification	2	Tooling pick-ups for all interfaces	40 hours		6m x 6m	0.05mm	Laser tracker
8	SML2 Jig Re-Certification		Tooling pick-ups for all interfaces	40 hours		6m x 6m	0.05mm	Laser Tracker Photogrammetry CMM
9	Product Assembly	2						
10	Remove product from Jig	2						
11	NDT	2						
12	Post -NDT	2	T-cleat positions, upper ring and external brackets		20 hours	4m x 4m	0.05mm	Laser Tracker Photogrammetry CMM
13	SML2 Jig Recertification	2	SM-CM brackets and SM rings	40 hours		6m x 6m	0.05mm	Laser Tracker Photogrammetry CMM

6.5. Step 11 (DfV): Simulate Verification Processes with Instrument Uncertainty Models

(See A4 and A5 in Section 2.5.1)

The instrument selection stage highlighted the potential for using a photogrammetric metrology system or CMM for aspects of the verification requirements as shown in Table 10. Following a design review with ADS, it became clear that using a CMM would not be cost effective so it was removed from the options matrix. The DfV trade-off database contained a simple to use tool for estimating instrument specific measurement uncertainty. A 'Metrology and Tooling Uncertainty Estimation' tab was created as a simple to use selection tool with instrument specific operating instructions to inform the designer on the processes involved. An extract of the tab can be seen in Table 11. The user is required to input the required measurement confidence interval and approximate measurement volume. The user values are used to calculate the estimated measurement uncertainty over the given volume. Whilst it does not provide an in-depth in-process measurement uncertainty estimation, it aids in quickly identifying the rough estimation of uncertainty of capable measurement instruments.

The results from the database revealed that both of the selected metrology instruments, the laser tracker and photogrammetry system, measured with an estimated uncertainty (±0.111mm and ±0.118mm, respectively, in Table 11) that was greater than the required tolerances when the measurement confidence interval was set to 2σ , detailed in Table 10. The DfV guidelines then take the designer into the Step 12 actions where questions are posed to aid in meeting requirements.

Table 11: Extract from DfV Trade-off Database Tab 'Metrology & Tooling Uncertainty'

FOR INFORMATION			Please select desired confidence level for assembly (σ)	Measured Distance(m)
Confidence Level	**Confidence Interval**	**Expected %Errors**	2	The measured distance is equal to that set on the SM Trade-off spreadsheet
1 σ	68.3%	31.7%		
2 σ	95.4%	4.6%		
3 σ	99.7%	0.3%		
4 σ	99.994%	0.006%		
5 σ	99.9999%	0.0001%	**2**	**5**
6 σ	99.9999998%	0.0000002%		**LINK**

	Photogrammetry			**Uncertainty Before Instrument Addition**		
Photogrammetry	***Component***	***Standard Uncertainty***		***Component***	***Standard Uncertainty***	
Assuming metrology process being as follows:	*SMR Magnetic Nests*	*2.4µm*	*2.4*	*SMR Magnetic Nests*	*2.4µm*	*2.4*
	Split Bearing Centering	*2.5µm*	*2.5*	*Split Bearing Centering*	*2.5µm*	*2.5*
	Split Bearing Pin Centering	*6µm*	*6*	*Split Bearing Pin Centering*	*6µm*	*6*
1. Jig/fixture set into position and alligned using a laser tracker.	*Instrument Uncertainty*	*5µm+5µm/m*	*30*			
	CTE: Temperature Probe +/-0.5K	10% 11µm	*1.1*	*CTE: Temperature Probe +/-0.5K*	10% 11µm	*1.1*
2. Photogrammetry system used for verification.	*Fit Residuals*	*50µm*	*50 µm*	*Fit Residuals*	*50µm*	*50 µm*
	Pressure and Thermal Effects	*1µm/m*	*8.8*	*Pressure and Thermal Effects*	*1µm/m*	*8.8*
3. Photogrammetry system used for recertification.	Combined Standard Uncertainty (µm)		+/- 59.4 µm	Combined Standard Uncertainty (µm)		+/- 51.3 µm
	Expanded Standard Uncerainty		**+/- 118.8 µm**	**Expanded Standard Uncerainty**		**+/- 102.5 µm**

	Laser Tracker			**Uncertainty Before Instrument Addition**		
Laser Tracker	***Component***	***Standard Uncertainty***		***Component***	***Standard Uncertainty***	
The process for setting and verifying a fixture with a laser tracker being as follows:	*SMR Magnetic Nests*	*2.4µm*	*2.4*	*SMR Magnetic Nests*	*2.4µm*	*2.4*
	SMR Centering	*6µm*	*6*	*SMR Centering*	*6µm*	*6*
	Instrument Uncertainty	*5µm + 3µm/m*	*22.5*			
1. Define datums on fixture, measure jig reference system, single position laser tracker	*Instrument Resolution*	*0.3µm*	*0.3*	*Instrument Resolution*	*0.3µm*	*0.3*
	CTE: Temperature Probe +/-0.5K	10% 11µm	*1.1*	*CTE: Temperature Probe +/-0.5K*	10% 11µm	*1.1*
2. Best fit to CAD (software analysis)	*Fit Residuals*	*50µm*	*50 µm*	*Fit Residuals*	*50µm*	*50 µm*
3. Set interfaces to required tolerance	*Pressure and Thermal Effects*	*1µm/m*	*8.8*	*Pressure and Thermal Effects*	*1µm/m*	*8.8*
4. Verify with laser tracker at specified tooling points	Combined Standard Uncertainty (µm)		+/- 55.9 µm	Combined Standard Uncertainty (µm)		+/- 51.2 µm
	Expanded Standard Uncerainty		**+/- 111.8 µm**	**Expanded Standard Uncerainty**		**+/- 102.4 µm**

6.5.1. Question B (DfV): Is the Process Capable?

The simulation results in Table 11 revealed that with the existing tooling design and measurement station positions, the process was not capable. The designer therefore passed down the ‘No’ route.

6.5.2. Question C (DfV): Does a Suitable Measurement Instrument Exist?

A laser tracker has been used for the existing E3000 assembly process and proven to be effective with respect to data acquisition. Following the implementation of Step 11 it became evident that the current measurement uncertainty exceeded the tolerance limits and therefore suggested that the process had potential for optimisation. For this reason, if the designer was to ascertain that the design was fixed with no room for modification to support verification requirements then the laser tracker would be passed down the ‘Yes’ route to optimise the measurement plan and reduce the in-process measurement uncertainty.
As the previous DfV guidelines revealed the potential for use of photogrammetry within the build sequence, ADS decided that the potential option would be explored.

6.5.3. Question D (DfV): What is the Limitation?

Based upon the results from the measurement simulation using data gathered from the previous Steps, the designer is taken to Question D. The DfV guidelines prompt the designer to consider three primary design limitations for verification (Steps 12a - c). Questions embedded in Steps 12a - c are in place to provoke a trade-off between the three areas.

6.5.4. Question E (DfV): Can the Metrology Process be Optimised?

The follow on section shows the route taken by the designer to go down the path for current process optimisation where the answer is ‘Yes’. Should the answer be ‘No’, the designer is guided back into Question D and the follow on Steps 12 A, B and C.

6.6. Step 12A (DfV): Reduce Assembly Tolerances

(See A5 in Section 2.5.1)

Following the DfV framework steps, if it was found that there was no capable metrology system and or process for dimensionally verifying the component assembly. It was proposed that there were three primary focal points that needed to be addressed (Step 12a - c). Addressing the assembly tolerances is an obvious choice, however, it can have significant impacts upon the structure design. In order to assess the feasibility of reducing the assembly tolerances a study was undertaken for the E3000 CM to Y Shear Wall interface as the key assembly features of this assembly joint represents the majority of the critical interfaces for the E3000 service module.

To ensure first time assembly of major spacecraft substructures which have not had prior trial assembly and to avoid fouls or induction of assembly stresses, an overall flatness tolerance of ±0.05mm was specified along panel interfaces up to 4m long. Achieving this tolerance has been shown to be challenging through the uncertainty analysis studies within the previous DfV steps and baseline uncertainty estimations (Table 8). Assembly jigs were measured, reworked and re-measured in the attempt to meet this tolerance requirement. Sample stress analysis performed for this study showed that the stresses resulting from ±0.1mm misalignment of the structure interfaces can be accommodated without unacceptable reduction in strength margins [109]. It was clear that the tolerances were 'over engineered', which has often been observed within aerospace engineering design due to the implications of wrongly altering a global tolerance. If it is found that a simple reduction in tolerances requirements can achieve the desired outcome or if the tolerances cannot be altered then the DfV process can be used to optimise the process from a metrology perspective. This approach was used.

6.7. Step 12B (DfV): Redesign assembly tooling and or process

(See A3 and A4 in Section 2.5.1)

The limiting factors within the current E3000 service module assembly processes, highlighted in Step 11, were primarily associated with the scale over which the tolerances need to be maintained as well as the allocated tolerances. The assembly is a typical Type 2 (see Section 2.3.3.1) in that tooling interfaces are required to be set to within ± 0.05mm to a datum that is up to 4m away and used to maintain assembly KCs. Through understanding the mapped requirements, detailed during Steps 7 and 8, the designer is led to understand where the areas of estimated high uncertainty are. Through the simulations undertaken within Step 11, the designer is shown the relationship between volume, uncertainty management and tolerance setting. Following the estimation of measurement uncertainty over a given volume, the designer is posed the question through the DfV framework regarding the redesign of assembly tooling and processes. If, as has been shown through the DfV process, the measurement uncertainty is unmanageable, then the design team need to either redesign the assembly tolerances, as in Step 12a, and or redesign the assembly tooling and or process. Within the assembly stages, the critical features reveal the areas of uncertainty that need to be measured and set with the assembly tooling as illustrated in Figure 51.

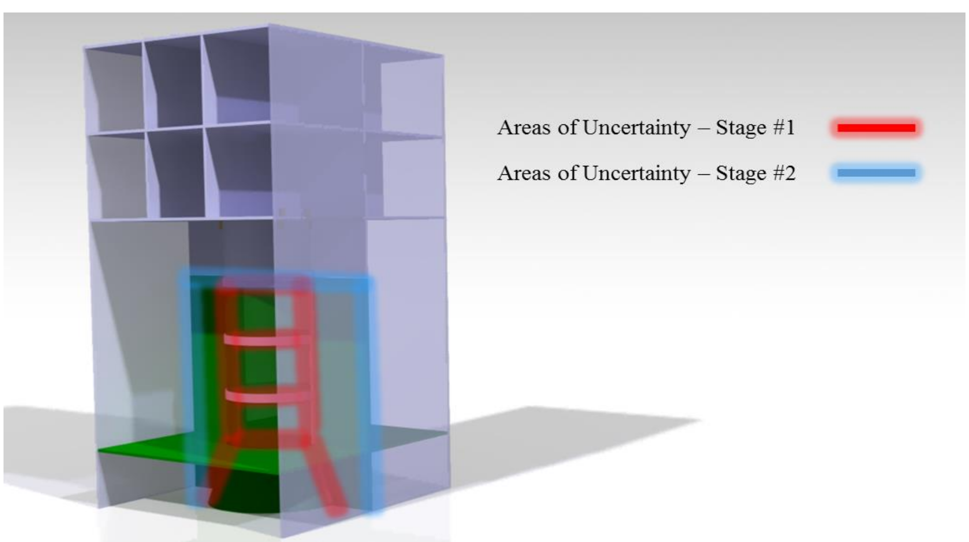


Figure 51: Highlighted areas of uncertainty during assembly stages 1 and 2.

During Stage 1, the critical features are the ring-to-ring interfaces and the cylinder-to-shear wall cleats. The central cone and cylinder is constructed from four sections. The key requirement is for the parallelism, position and flatness to be maintained over the highlighted areas. Through estimating the stack up of dimensional variation due to the measurement uncertainty build up within the structural assembly, the designer is led to propose methods for uncertainty reduction within tooling design. The current assembly process uses an assembly jig that holds all of the SML1 components within nominal positions whilst they are assembled. The jig is set to nominal position with the use of the laser tracker. Each interface that is set has a degree of uncertainty and error. In order to reduce the assembly uncertainty, the designer can seek to reduce the number of interfaces that require adjustment which in turn also reduces the set-up costs. The central cone-cylinder construction is largely symmetrical. It is designed this way to provide high load bearing capability, deviation from the nominal symmetry results in undesirable induced stresses during take-off and stage separation during satellite launch. To reduce assembly uncertainty, the designer can utilise symmetry within tooling design to reduce the number of interfaces that require setting with the aid of external metrology.

By following this process, the author created two alternative assembly methods from which the following proposals were formed. The purpose of Step 12b within the DfV guidelines is to generate design ideas based upon metrology data to further inform the tooling designer as to best practice from a metrology perspective.

The following sections detail proposals that consider metrology processes and measurement uncertainty as the primary focus within assembly. Within a multidisciplinary design team, the ideas were then traded off against other DfX criteria as directed within the DfV process flow, Decision ‘A’. The concepts are summarised, followed by a detailed discussion on how they could be implemented.

6.7.1. Assembly Proposal 1 Summary

Assembly Proposal 1:‘Part-to-part Interchangeability’ focuses upon Step 12b, Question (a) within the DfV guidelines. In order to reduce the volumes over which measurements are required for tool setting and component stage verification, the author proposed manufacturing smaller high accuracy sub-assemblies with embedded measurable KCs to reduce the estimated uncertainty from thermal variation and laser tracker distance measurement. In final assembly, tooling can be reduced with ‘loose’ sub-assembly holding fixtures. The uncertainty budget for the assembly proposal was calculated (see Table 14). More details of this is shown in Section 6.7.3. The data from the uncertainty budget would subsequently be used to inform the tolerancing engineer as part of Question A in the following DfV Step, outside of scope of the DfV framework.

6.7.2. Assembly Proposal 2 Summary

> Assembly Proposal 2: ‘Integrated Assembly Cell’ focuses upon Step 12b, Question (b) within the DfV guidelines. In order to reduce verification requirements for structure assembly stages and customer design alterations, a concept to directly load sub-assembly fixtures into the final stage assembly cell was proposed. An integrated assembly cell was designed to create a streamlined flow system whereby E3000 sub-assemblies translate between assembly stations and sub-assembly fixtures integrate directly into an assembly arena reducing tooling and decreasing certification and verification processes. More details of this proposals are given in Section 6.7.4.

6.7.3. DfV - Assembly Proposal 1

Reliance on monolithic jigs during construction of the E3000 has rendered assembly limitations as the current jigs are highly inflexible, costly and have long lead times for design, alterations and commissioning. The root causes are the difficulties in maintaining demanding tolerance requirements over large structures and the high quantity of manual operations for relatively low production volumes.

The DfV guidelines revealed that the existing E3000 assembly processes are not capable for proving conformance. The measurement uncertainty is too large with respect to the design tolerances. In order to resolve this, the designer is prompted to address the design tolerances as in Step 12a, then address the assembly methods to reduce the volumes over which assembly fixtures are required to maintain critical tolerances.

Assembly Proposal 1 aims to separate the existing assembly process into smaller sub-assemblies to reduce measurement volumes and respective potential thermal variation across large jigs, highlighted as the dominant source of uncertainty. The proposal seeks to introduce part-to-part assembly and interchangeability, currently not widely realised in the aerospace industry [23], as a route to achieving cost effective product conformance. The goal of this assembly proposal was to move away from large monolithic jigs that are used to maintain critical tolerances for each stage of the satellite assembly and move to a simpler jig that can accommodate assembly of smaller sub-assembly structures. This requires the design of high accuracy fixtures of a smaller scale that can maintain challenging tolerances for critical interfaces. This proposed solution asks if it is possible to maintain tight tolerances during sub assembly phases so that the final assembly can be constructed in a ‘loose’ assembly jig without the requirements for external metrology. This would be made feasible through designing one way assembly features such that the verification of the assembly conformance is implicit upon successful joining of sub-assemblies.

In order to accommodate allowances for product variation, it was proposed that all sub-assemblies be constructed from reconfigurable tooling, using enhanced metrology techniques such as laser tracker networking to achieve accurate and precise sub-assemblies [51].

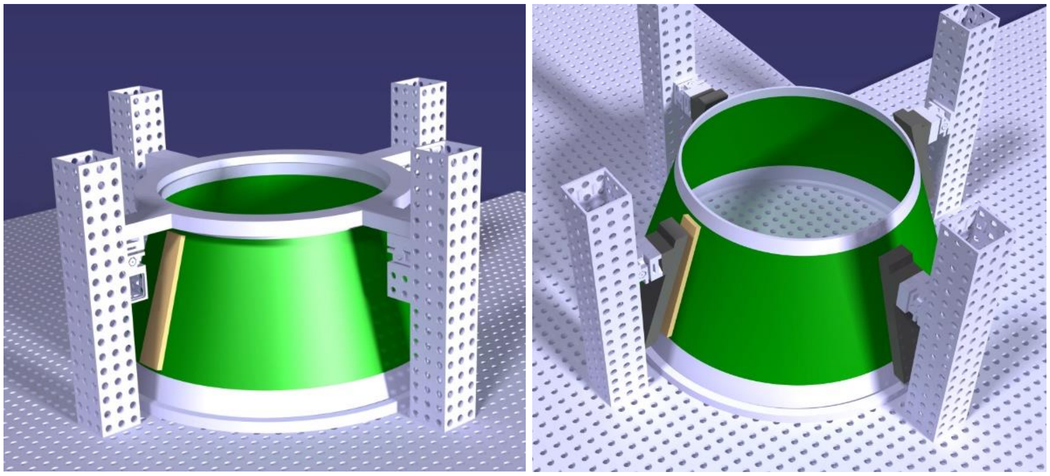


Figure 52: Assembly Proposal 1 conceptualisation: Reconfigurable tooling for sub-assembly of rings and T-cleats to SML1 cone on floor mounted grid plate tooling.

Assembly Proposal 1 for the service module cone and cylinder is illustrated in Figure 52 and Figure 53 respectively. This sub-assembly includes the bonding of upper and lower rings as well as T-cleats. The LVA base ring fixture is positioned on a grid with four bars vertically protruding, which accommodate a suite of fixture variations including the cradles for the upper ring fixation and the T-cleat bonding processes. The design includes the use of 6DOF manipulators to remove positional accuracy degradation built up from the relatively rough setting process of the vertically protruding columns. The tooling interfaces are equipped with an H7 toleranced hole pattern to integrate directly with the reconfigurable tooling [110]. The fixtures can be reconfigured for any structural design variation requiring only new bespoke interface plates for each build, design dependent.

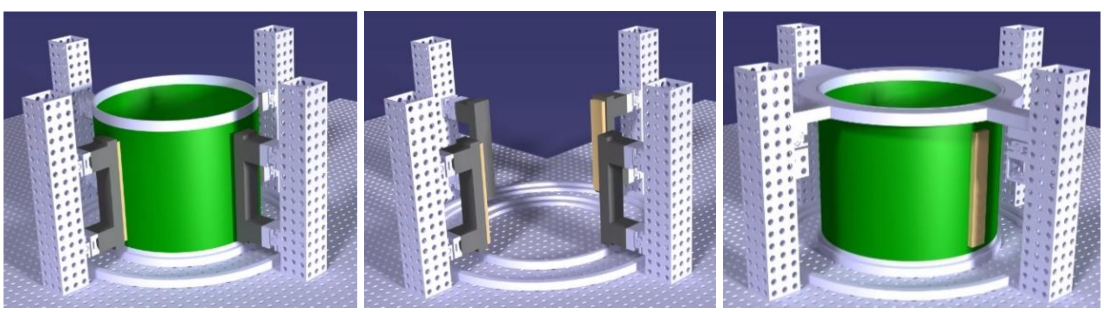


Figure 53: Assembly Proposal 1 conceptualisation: Reconfigurable tooling for sub-assembly of rings and T-cleats to SML1 cylinders.

The Assembly Proposal 1 bracket bonding fixtures (Figure 54) contain design similarities to the current approach but have replaced the inflexible steel bars with a reconfigurable, modular design to reduce tooling requirements.

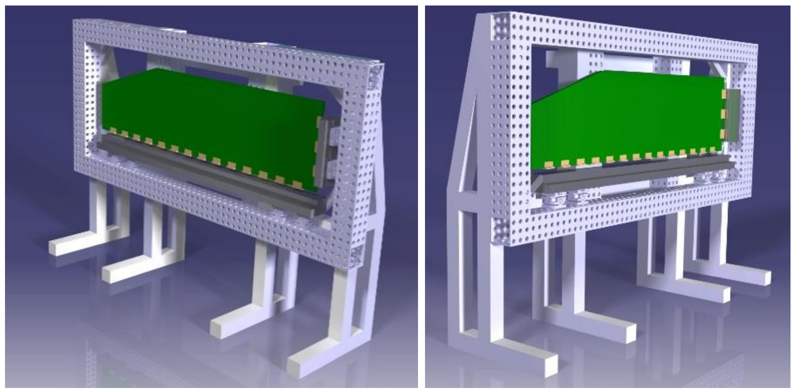


Figure 54: Assembly Proposal 1 conceptualisation: Reconfigurable tooling for sub-assembly of brackets to SML1 panels.

The introduction of smaller sub-assemblies generates greater requirements for verification. This is because the reconfigurable tooling is generally less stable than steel welded bespoke fixtures and increased sub-assemblies mean increased measurement requirements. To accommodate this, the author proposed photogrammetry as a means to rapidly certify the sub-assemblies prior to integration. Utilisation of photogrammetry requires consideration within the design phase for effective integration with a laser tracker reference network. Measurable KCs need to be designed into the external mates to enable efficient use of photogrammetry.

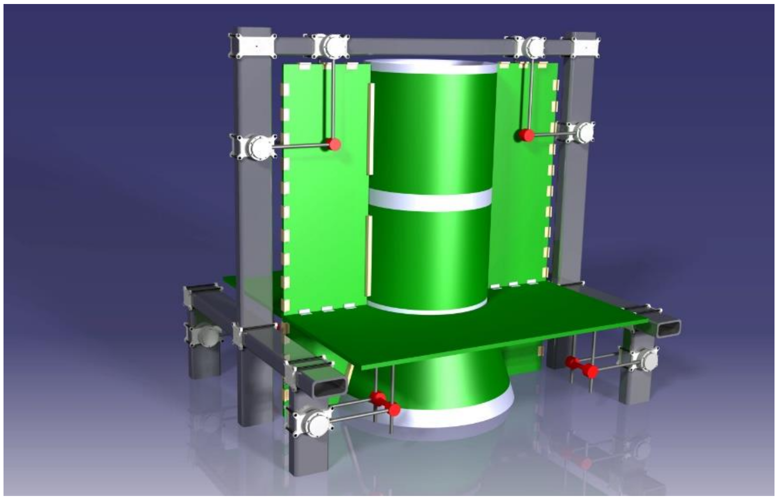


Figure 55: Assembly Proposal 1 conceptualisation for visualisation purposes: Loose work holding fixture to support part-to-part assembly for SML1 during final assembly and integration.

Figure 55 illustrates a conceptualisation for the proposed ‘loose’ tooling method for the final process steps within Assembly Proposal 1. This concept perpetuates the philosophy of part-to-part assembly by providing simple support to the sub-assemblies as they are positioned accurately with embedded structural assembly location features made possible through the high accuracy sub-assembly components. The large “loose” jig acts only for support and does not provide positional verification. It is an illustration of a structure composed of BoxJoint, manufactured by DELFOi [69]. The BoxJoint structure provides a housing/scaffolding for articulating arms which hold the sub-assemblies at datum holes and allow the manual manipulation of the panels into position by an operator.

The estimated build uncertainty for Assembly Proposal 1 has been calculated as shown in Table 13, Table 14 and Table 15.

Table 12: Assumptions for uncertainty calculations used within Assembly Proposal 1 [45], [57], [108], [111].

Assumptions		
Parameter	**Value**	**Units**
Temperature Variation during setting	0.50	°C
Temperature Variation during build	0.50	°C
Assembly Jig Height	1.00	m
Laser Tracker Distance	2.00	m
Laser Tracker Base Uncertainty	15.00	µm
Laser Tracker Uncertainty	6.00	µm/m
Steel CTE	12.00	µm/m/°C
CFRP CTE	6.00	µm/m/°C
Aluminium CTE	24.00	µm/m/°C
Photogrammetry Base Uncertainty	10.00	µm
Photogrammetry Uncertainty/m	10.00	µm/m
Thermal Scaling	90.00	%
Main Assembly Height	3.00	m

Table 13: Uncertainty estimation calculation for the setting of each sub-assembly fixture. It is widely accepted that thermal expansion compensation within commercial laser tracker software can be used effectively with a 90% accuracy over small volumes [112].

Sub-Assembly Fixture Setting - Aluminium					
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertainty**	
Laser Tracker Alignment	20.00	Normal	2.00	10.00	µm
Laser Tracker	27.00	Normal	2.00	13.50	µm
SMR Centering	6.00	Normal	2.00	3.00	µm
Drift Nest Centering	6.00	Normal	2.00	3.00	µm
Tool Setting Tolerance	40.00	Rectangular	1.73	23.09	µm
Thermal Expansion (Compensated)	1.20	Normal	2.00	0.60	µm
			Standard Uncertainty	**28.88**	µm
			Expanded Uncertainty (k=2)	**57.76**	µm

Table 14: The stack of the sub-assemblies results in an estimated build uncertainty of ±0.115mm which is a reduction of approximately 0.06mm from the baseline process uncertainty.

Combination of Sub Assemblies				
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertainty**
Build Variation	57.76	Normal	2.00	28.88 µm
Longest Component Stack	4.00	N/A	N/A	N/A µm
			Standard Uncertainty	**57.76** µm
			Expanded Uncertainty (k=2)	**115.51** µm

Table 15: Measurement uncertainty estimation using the GUM method for the proposed photogrammetry technology insertion during rapid dimensional verification of the final assembled structure.

Completed Build Rapid Health Check				
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertainty**
Photogrammetry	40	Normal	2	20.00 µm
SMR Centering	6	Normal	2	3.00 µm
Thermal Expansion (Compensated)	1.8	Normal	2	0.90 µm
			Standard	**20.24** µm
			Expanded	**40.49** µm

6.7.4. DfV - Assembly Proposal 2-1

Assembly Proposal 2 Iteration 1 (AP 2 –1) primarily focuses upon Step 12b question (b): Can assembly jigs be reutilised through the assembly flow to reduce further variation from tooling alignment uncertainty? To reduce measurement uncertainty, the integrated assembly cell (IAC) draws upon a variety of well-established assembly techniques and integrates them in such a way to produce an innovative assembly method relevant to spacecraft production. In order to reduce the reliance upon high accuracy tooling, an integrated metrology rotary table was proposed to decrease laser tracker verification tasks, minimising the amount of symmetrical tools that require setting. A metrology rotary table is indexed with a quantified accuracy and uncertainty that is small in comparison to the uncertainty of setting symmetrical tooling with a laser tracker [111]. Time is saved through tooling reduction and assembly accuracy is improved through reducing potential error sources.

The primary objective for the IAC was to incorporate translation of either the satellite between assembly stations or the sub assembly fixtures into the IAC, as to act similar to a pulsed assembly line, most popularly seen within the automotive industries and state of the art fighter aircraft assembly [78]. To enable this, and to meet the demanding tolerance requirements set within aerospace assemblies, a high precision rotary table with an integrated air flotation and rail system was introduced as the primary mechanism for the translation of the spacecraft structure between assembly stations. For the alternative option of translating the sub assembly fixtures into the main assembly cell (MAC), zero-point clamping technology was integrated into the design of the sub-assembly fixtures to allow a sufficiently rapid detachment and translocation option. This allows the structure body to remain on the same assembly platform between builds. This presents an advantage over the physical translation of core structures between a static fixture onto another, due to the decrease in uncertainty build up from the base ring fixtures.

As the spacecraft translation strategy presents an increased degree of flexibility during the assembly flow, other fixtures within the assembly stages can be designed with further advantages. This permits the use of large monolithic tooling with the integration of reconfigurable and modular elements. The purpose of the MAC is to develop a proposal that shifts from large monolithic, inflexible jigs to decrease the required tooling, whilst enabling tight tolerance capability at the critical interfaces. The key driver behind the conceptual design of AP 2 - 1 was the reduction of dimensional verification tasks with increased rate and accuracy capability. The following gives a series of illustrations representing the first iteration of AP 2 – 1, which was designed on the concept of translating spacecraft structures on a high precision metrology rotary table between structural build stages.

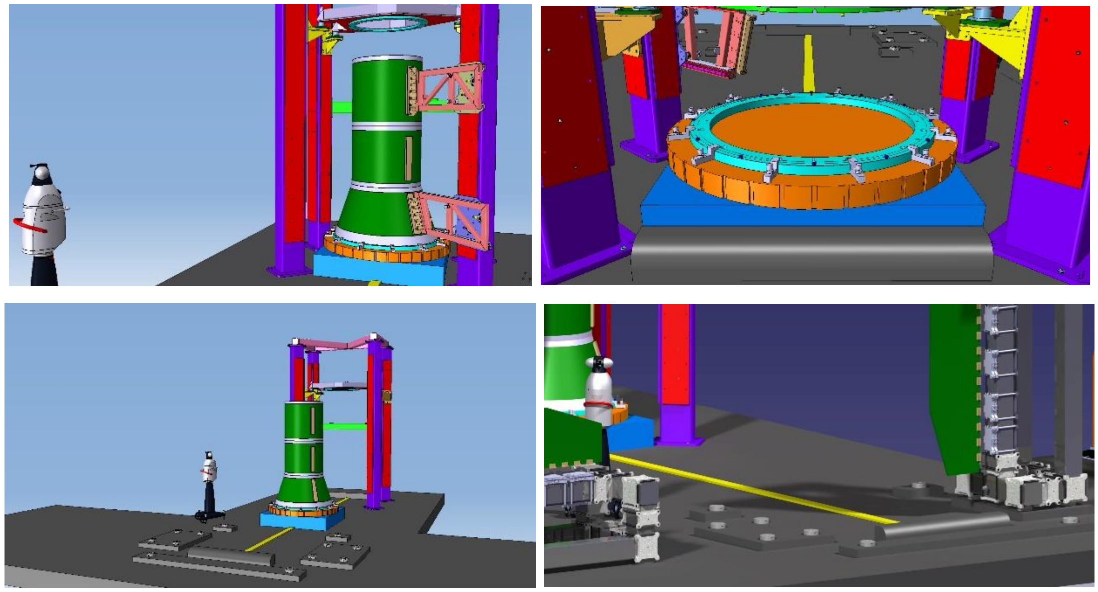


Figure 56: AP 2 - 1 first iteration visualisation. Use of metrology rotary table to reduce assembly tooling.

Figure 56 illustrates the initial concept for AP 2 –1. The rotary table utilises an air flotation mechanism, guided by a floor mounted rail to translate the satellite between assembly stations. The two stations incorporate highly reconfigurable tooling so that the concept can support any structural design variation within the limits of the rotary table capabilities. A metrology rotary table allows for axisymmetric assembly to proceed with reduced tooling and enhanced verification.

The two stations are situated within an array of zero-point clamps, which host the reconfigurable structures upon delivery. Zero-point clamps have a high repeatability in the order of 5 microns, as well as the ability to carry heavy loads, up to 105kN [1]. The clamps can provide the mechanical basis for the integrated loading of sub-assembly fixtures into the assembly cell.

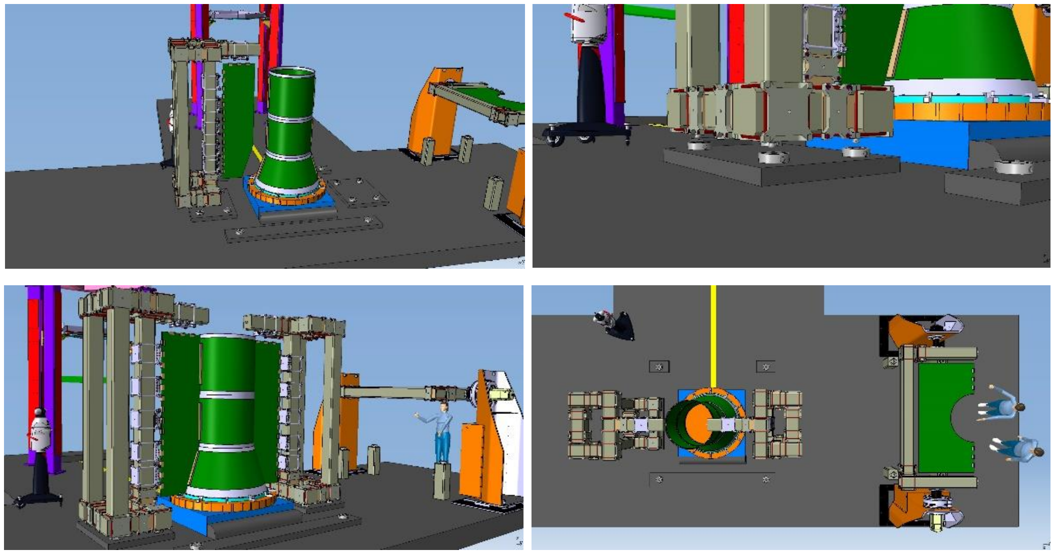


Figure 57: Assembly Proposal 2 –1, first iteration visualisation. Spacecraft structure translation between assembly stages on high accuracy metrology rotary table to reduce inter-jig variation. Use of floor mounted zero-point clamps as local datum features for rapid jig location and panel assembly.

Figure 57 displays a series of fixtures designed using BoxJoint [69] components that hold the repeatable tooling on the spacecraft base. The base is used as a reference during the fixture construction and certification process. Through this process it is proposed that the satellite sub-assembly component can be held within a known reference frame whilst translated between assembly stages to reduce tooling and tooling redundancy.

6.7.5. DfV – Assembly Proposal 2 - 2

Through a multi-disciplinary design team trade-off workshop held at ADS, this process was refined. It was decided that the satellite structure should remain in a single station to further utilise the integrated loading concept of bringing pre-set fixtures to the assembly cell. This in effect led to the creation of the single station main assembly super cell (MASC), Assembly Proposal 2 –2 (iteration 2). The second iteration of Assembly Proposal 2 (AP 2-2) utilises reconfigurable tooling for every stage of the assembly such that the process sequence resembled that of the current E3000 assembly method with reduced tooling and improved fixture utilisation.

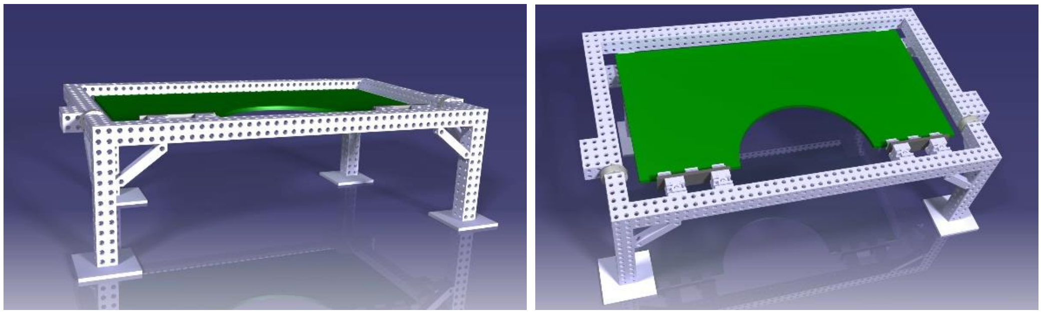


Figure 58: Assembly Proposal 2-2 second iteration visualisation: Reconfigurable bracket bonding jigs with integrated zero-point clamps to reduce laser tracker verification tasks by reutilising tooling to maintain critical interfaces of SM floors within known locations.

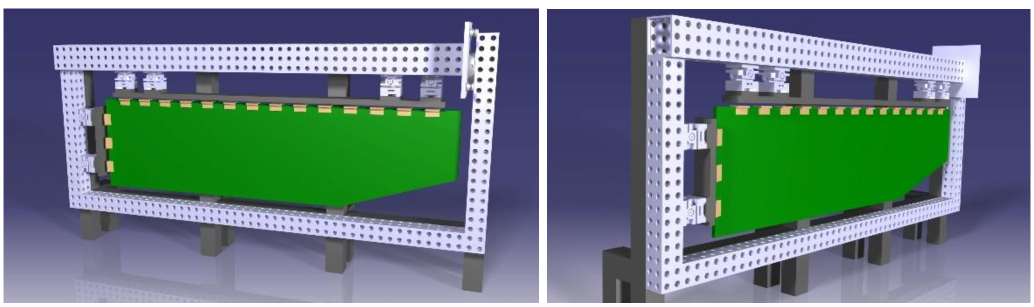


Figure 59: Assembly Proposal 2-2 second iteration visualisation: Reconfigurable bracket bonding jigs with integrated zero-point clamps to reduce laser tracker verification tasks by reutilising tooling to maintain critical interfaces of shear walls within known locations.

Figure 58 and Figure 59 represent the tooling concept to permit fixture sections to be released from static locations and translated into secondary assembly stations whilst holding critical interface tolerances within the assembly tooling. End plates support integrated zero-point clamps and pins that create the hard points for a reference frame within the fixture during certification so that the panels have a known position relative to the clamps. This allows the detachable fixtures to be repositioned into the MASC whilst maintaining the location of the sub-assembled panels.

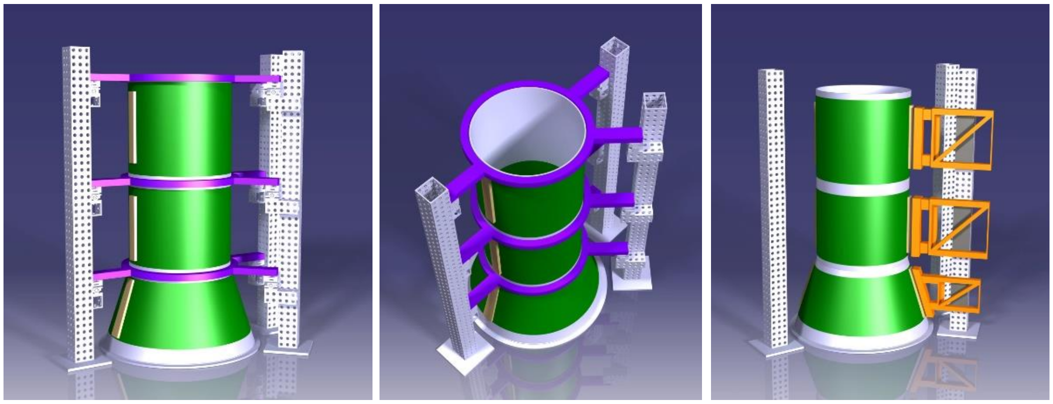


Figure 60: Assembly Proposal 2-2 conceptual visualisation. Plug and play tooling columns used to enable single station assembly to reduce laser tracker verification tasks.

The central cone/cylinder structure of the spacecraft structure is assembled in a similar fashion to the current E3000 - with cradles supporting the rings and hard tooling on slide ways for the T-cleat bonding processes. The major difference between the current assembly process and AP 2-2 is that the pillars are fully reconfigurable and removable to allow for product variants and rapid tool changeover with minimal verification requirements. This allows for the assembly of a variety of structural variations. Modular pillars configured around a central assembly station permit increased degrees of freedom for design flexibility.

Following the assembly of the central structure, the pillars have the capability to retract on slide ways enhanced with zero-point clamps for positional repeatability up against a repeatable hard stop. To increase stability and provide a flat assembly bed for the MASC, a granite base has been proposed. Granite is a dense material with a low CTE. Figure 61 shows an illustrated conceptual sequence displaying the next stages of assembly within the MASC.

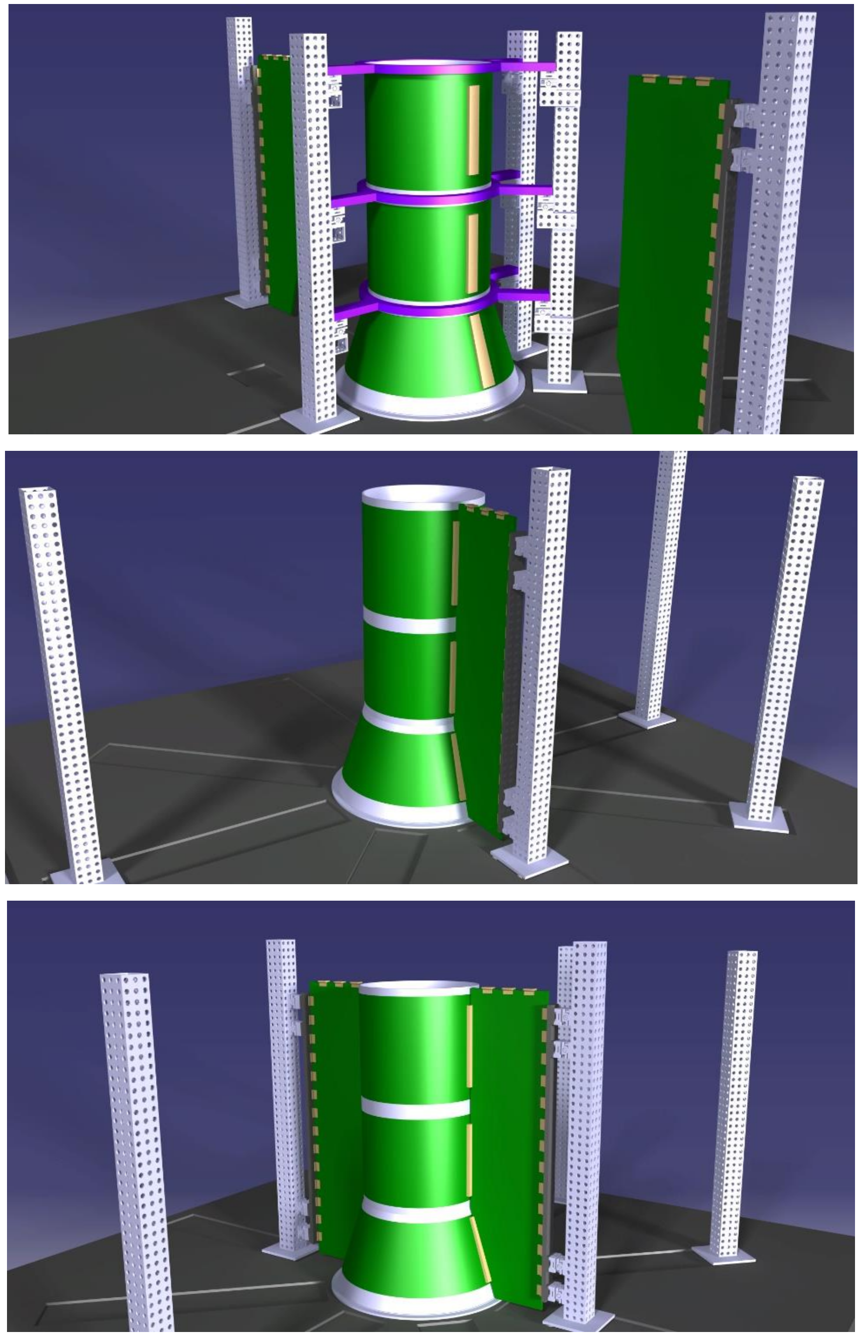


Figure 61: Assembly Proposal 2 -2 - Main Assembly Super Cell to enable spacecraft structure to remain in-situ as opposed to translating the structure between assembly stages as within current assembly builds.

The removal of the cradles and T-cleat bonding fixtures allows the pillars to slide/relocate within the MASC to a position, as to not interfere with the following assembly stages. The detachable section of the bracket bonding fixture can then be positioned within the MASC and brought to the correct position with the aid of the repeatable tooling such as zero-point clamps. To enable the increased verification requirements within this iteration, photogrammetry was proposed for rapid verification of fixture interfaces.

Following the shear wall attachment to the central cone/cylinder structure, the tooling is retracted to enable assembly of the SM floors. To permit the satellite structure to index and maintain stability of the SM shear walls, dummy tooling is introduced for support. The floors are then introduced into the MASC using the same process as the shear walls.

The use of the rotary table within the MASC was primarily to reduce tooling and verification processes with the added gain of being able to remove the requirement for multi-access lifting equipment. Within the current spacecraft assembly and integration facility the geometry of the ceiling will only permit a single axis crane. If this were to change, the MASC would not require the rotary table for this assembly iteration although it is supported from a metrology perspective as it decreases tool setting requirements, increases fixture modularity and supports the potential for product variants.

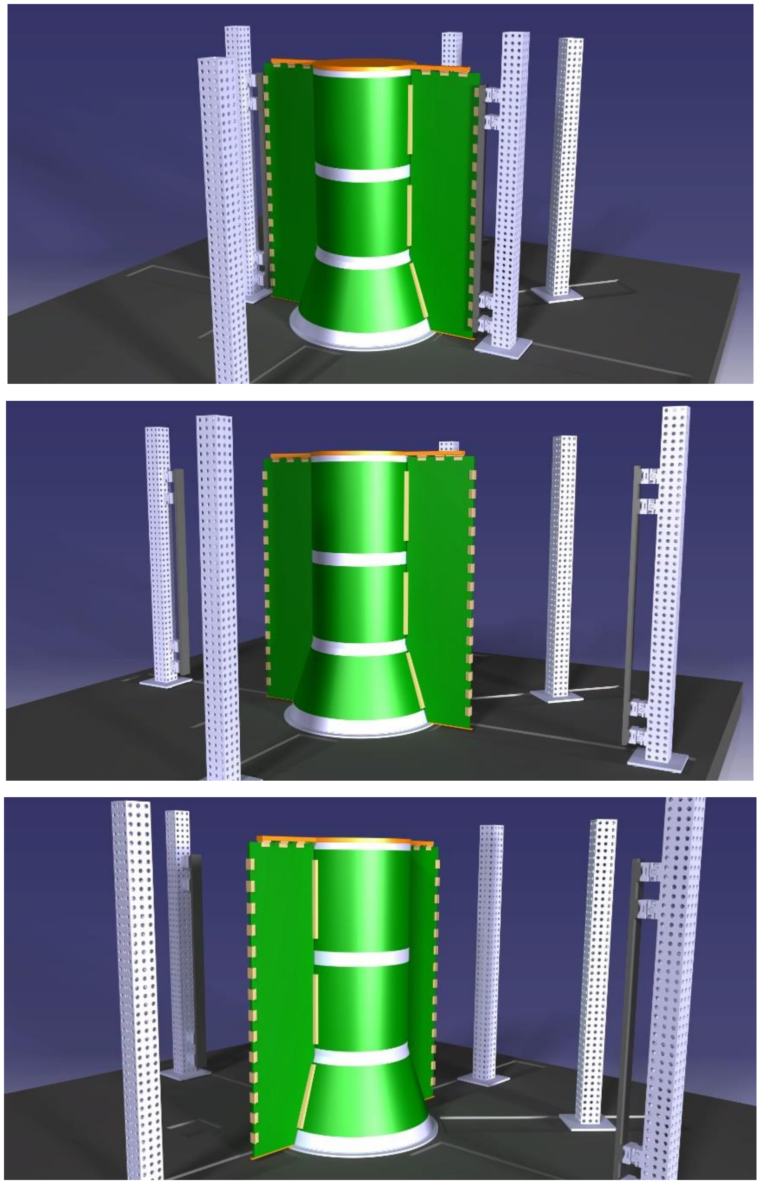


Figure 62: Assembly Proposal 2 -2 - Dummy tooling used to stabilise shear walls during indexing with plug-and-play tooling pillars to increase design flexibility and improve efficiency.

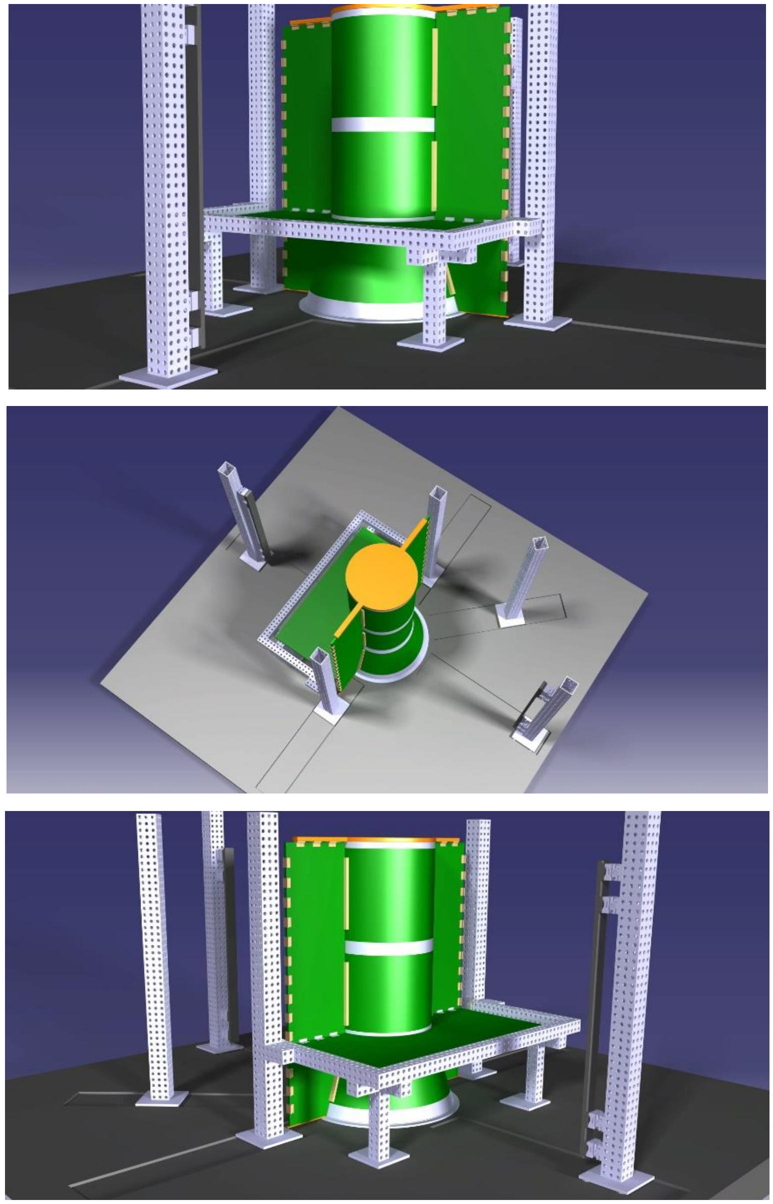


Figure 63: Assembly Proposal 2-2 - Conceptual reconfigurable modular pillars used for integration and assembly of SM shear walls and floors.

Table 16: Assumptions for uncertainty calculations used within assembly proposal 2 –1 [45], [57], [108], [111].

Assumptions		
Parameter	**Value**	**Units**
Temperature Variation during setting	1.50	°C
Temperature Variation during build	3.00	°C
Assembly Jig Height	3.00	m
Laser Tracker Distance	3.00	m
Laser Tracker Base Uncertainty	15.00	µm
Laser Tracker Uncertainty	6.00	µm/m
Steel CTE	12.00	µm/m/°C
CFRP CTE	6.00	µm/m/°C
Aluminium CTE	24.00	µm/m/°C
Photogrammetry Base Uncertainty	10.00	µm
Photogrammetry Uncertainty/m	10.00	µm/m
Thermal Scaling	90.00	%
Main Assembly Height	3.00	m
1 Arcsecond	4.85	µRad
0.5 Arcseconds	2.42	µRad

Table 17: Uncertainty estimation calculation for the setting of each sub-assembly fixture for assembly proposal 2 -1. It is widely accepted that thermal expansion compensation within commercial laser tracker software can be used effectively with a 90% accuracy over small volumes [78].

Main Assembly Fixture Setting - Steel Pillars				
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertainty**
Laser Tracker Alignment	20.00	Normal	2.00	10.00 µm
Laser Tracker	33.00	Normal	2.00	16.50 µm
SMR Centering	6.00	Normal	2.00	3.00 µm
Drift Nest Centering	6.00	Normal	2.00	3.00 µm
Tool Setting Tolerance	50.00	Rectangular	1.73	28.87 µm
Thermal Expansion (Compensated)	5.40	Normal	2.00	2.70 µm
Rotary Table Coning	14.54	Normal	2.00	7.27 µm
			Standard Uncertainty	35.83 µm
			Expanded Uncertainty (k=2)	71.66 µm

Table 18: AP 2 -1: Uncertainty analysis of structural build. During the structural assembly of the E3000 within the MAF, the thermal CTE differences between the steel fixture and the carbon fibre structure presents a large uncertainty. Historic measurement data sets have shown that the thermal variations can be up to 3℃ during structure build.
***N.B.** Thermal expansion disparity = (CTE difference between steel and carbon fibre) **x** (jig height) **x** (temperature variation).*

Main Assembly Fixture Build Variation				
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertainty**
Fixture Setting Uncertainty	71.66	Normal	2.00	35.83 µm
Thermal Expansion Disparity	54.00	Normal	2.00	27.00 µm
			Standard Uncertainty	44.86 µm
			Expanded Uncertainty (k=2)	**89.73** µm

Table 19: Uncertainty estimation for a rapid photogrammetry measurement of the assembly tooling to support the build sequence for AP 2 –1 steel.MPE values assumed for photogrammetry at the maximum distance of 3m based upon the assembly height.

Completed Super-Cell Rapid Health Check				
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertainty**
Photogrammetry	40.00	Normal	2.00	20.00 µm
SMR Centering	6.00	Normal	2.00	3.00 µm
Thermal Expansion (Compensated)	3.60	Normal	2.00	1.80 µm
MAF Setting Uncertainty	71.66	Normal	2.00	35.83 µm
			Standard Uncertainty	41.18 µm
			Expanded Uncertainty (k=2)	82.36 µm

Table 20: Uncertainty estimation for a rapid photogrammetry measurement of the spacecraft structure to support the build sequence for AP 2 -1 steel.MPE values assumed for photogrammetry at the maximum distance of 3m based upon the assembly height.

Completed Build Rapid Health Check				
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertianty**
Photogrammetry	40.00	Normal	2.00	20.00 µm
SMR Centering	6.00	Normal	2.00	3.00 µm
Thermal Expansion (Compensated)	1.80	Normal	2.00	0.90 µm
			Standard Uncertainty	20.24 µm
			Expanded Uncertainty (k=2)	40.49 µm

6.7.6. Overview of Design Proposals

In the preceding sections, assembly methods and tooling concepts were proposed from a metrology based perspective. Three proposals were identified and presented: Assembly Proposals 1, 2-1 and 2-2.

The uncertainty budgets for each assembly proposal were calculated to compare against the existing process (see Table 8). The uncertainty budgets were calculated using three different fixture materials to compare the effect of assembly tooling CTE on estimated product variation as thermal variation was highlighted as a major source of uncertainty. The three materials aluminium, steel and CFRP were selected due to availability within aerospace tooling industries. The materials were also chosen because steel has an approximately 50% smaller CTE than aluminium with CFRP having an approximately 50% smaller CTE than steel [108]. The following is a summary of the proposals given.

The design input summary from the DfV guidelines to support AP 1 is as follows:

1. Use of reconfigurable sub-assembly fixtures that can be maintained to high degrees of accuracy due to the comparatively small scale of the fixtures (see Objective 1, 2 and 3 Section 1.4, A.4 Section 2.5.1).
2. Design requirements for embedded location features within each sub-assembly to support part-to-part assembly (see Objective 4 and 3 Section 1.4, A.1 and 3 Section 2.5.1).
3. Location feature KCs to act as datums for rapid verification and dimensional inspection based on selected metrology instrument to reduce verification timescales and measurement uncertainty (see Objective 4 and 3 Section 1.4, A.1 and 3 Section 2.5.1).
4. Minimise assembly tooling required for final assembly through a combined Type 2 and part-to-part assembly method (see Objective 4 and 3 Section 1.4, A.1 and 3 Section 2.5.1) to reduce production tooling costs.

The design input summary from the DfV guidelines to support AP 2-1 is as follows:

1. Reduced laser tracker tasks through reutilising tooling (see A4 in Section 2.5.1)
2. Reduced assembly variation through integration of a metrology rotary table (see Objective 1 in Section 1.4 and A4 in Section 2.5.1)
3. Use of common tooling datum between assembly stages to reduce uncertainty stack-up from product translation (see Objective 4 and 3 in Section 1.4 and A4 in Section 2.5.1).

The design input summary from the DfV guidelines to support this AP 2-2 is as follows:

1. Reduced laser tracker tasks through reutilising tooling and reducing assembly footprint (see Section 2.5.1)
2. Reduced assembly variation through integration of a metrology rotary table (see Objective 1 in Section 1.4 and A4 in Section 2.5.1)
3. Use of common tooling datum between assembly stages to reduce uncertainty stack-up from product translation (see Objective 4 and 3 in Section 1.4 and A4 in Section 2.5.1).
4. Reduced assembly footprint through plug and play tooling concept.

Table 21: Uncertainty estimation for each assembly proposal: AP 1, AP 2-1 and AP 2-2. The MAF refers to the commissioning of the final assembly tooling and the Main Assembly Tool refers to the metrological verification.

Summary of Uncertainty at Critical Assembly Stages (µm) (k=2)											
		Current	**Proposal 1**			**Proposal 2 – 1**			**Proposal 2 – 2**		
Process		**Steel**	**Al**	**Steel**	**CFRP**	**Al**	**Steel**	**CFRP**	**Al**	**Steel**	**CFRP**
Build	**MAF Setting**	116.32	N/A	N/A	N/A	72.27	71.66	71.51	70.79	70.17	70.01
	Sub Assembly Tool Setting	N/A	57.76	57.75	57.74	N/A	N/A	N/A	N/A	N/A	N/A
	Completed Build	**177.85**	**115.51**	**115.49**	**115.49**	**177.39**	**89.73**	**71.51**	**176.79**	**88.54**	**70.01**
% Reduction from Baseline			*35.05%*	*35.06%*	*35.06%*	*0.26%*	*49.55%*	*59.79%*	*0.60%*	*50.22%*	*60.63%*
Rapid Verify	**Main Assembly Tool**	N/A	N/A	N/A	N/A	83.13	82.36	82.17	81.85	81.07	80.88
	Sub Assembly Tooling	N/A	20.96	20.88	20.24	N/A	N/A	N/A	N/A	N/A	N/A
	Completed Build	N/A	40.49	40.49	40.49	40.49	40.49	40.49	40.49	40.49	40.49

The estimated uncertainty results revealed that AP 1 offers benefits by minimising laser tracker measurement uncertainty through redefining the assembly sequence to enable part-to-part assembly. Changing the tool material does not appear to have a large impact due to the scale of the fixtures within AP 1. The tool material for AP 2 has a significant impact upon estimated build uncertainty due to the scale of the final assembly fixture.

The uncertainty of AP 2-1 is marginally more than that of AP 2-2 due to the coning effect of the rotary table as it spins [111] although it is considered minimal in comparison to the cost benefits that are gained through the integration of the rotary table by reducing tooling and laser tracker operations. Redesign of the assembly tooling and sequence from a metrology based perspective led to the proposal of multiple hardware recommendations and process considerations.

6.8. Step 12C (DfV): Embed Instrument Specific Measurement Features

(See A1, A2, A5 in Section 2.5.1)

The use of laser tracker technology within tool setting is critical within each of the Assembly Proposals, presented within Step 12b as it is the only capable instrument currently available on the market for that purpose against the requirements. The use of photogrammetry was recognised as a potentially cost beneficial option as it could reduce tool and product verification timescales. However, the use of photogrammetry requires design alterations to be utilised efficiently. This created the case for embedding features within the assembly tooling that could be used for direct measurement of critical features using both laser trackers and photogrammetry systems. The critical assembly features as highlighted in Figure 48 (Section 6.1) need to be designed such that the key characteristics are directly held in the fixture by a point that is directly measureable so that the datum structure can be directly translated through the assembly build by measurable features. This is critical as revealed within the case studies of state of the art aerospace programs which did not consider this within the early design phase. The two metrology systems identified for use within AP1 and 2 are laser trackers and photogrammetry. Methods have been created to combine systems measurement which are drawn upon for the technology demonstrator, requirements detailed in Table 22 (see Section 6.9.1). The methods established are as shown in Figure 64. The proposed process for simplifying the measurement of the spacecraft structure with both measurement systems is to design alternative fasteners to replace four fasteners with threaded datum pins seen in Figure 65. This simply adds a doweled section to the insert so that the fastener can provide precision location as well as clamping.

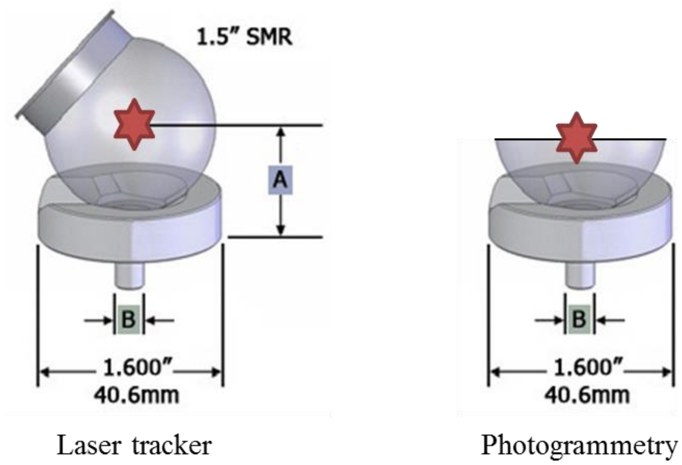


Figure 64: Method for the referencing of laser tracker measurements with photogrammetry measurements. The red stars show the areas directly measurable by each system respectively. The laser tracker measures the centre of the SMR and the photogrammetry system measures the centre of the BMR. Image adapted from [50].

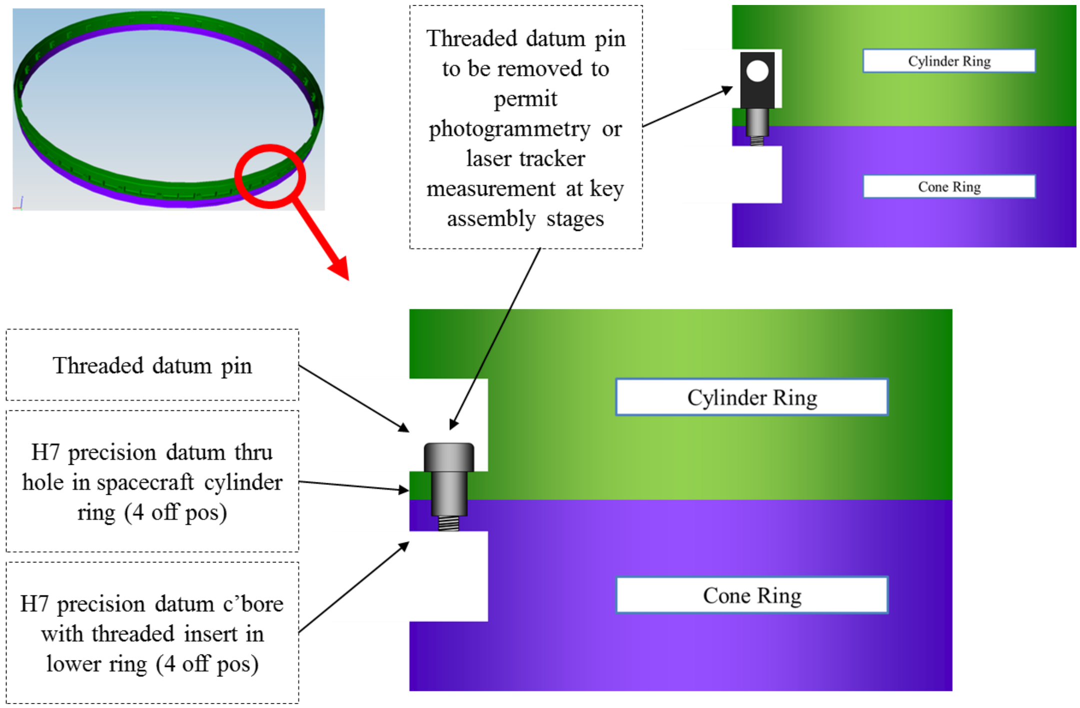


Figure 65: Conceptual proposal for the integration of embedded metrology datums for spacecraft structure assembly and verification.

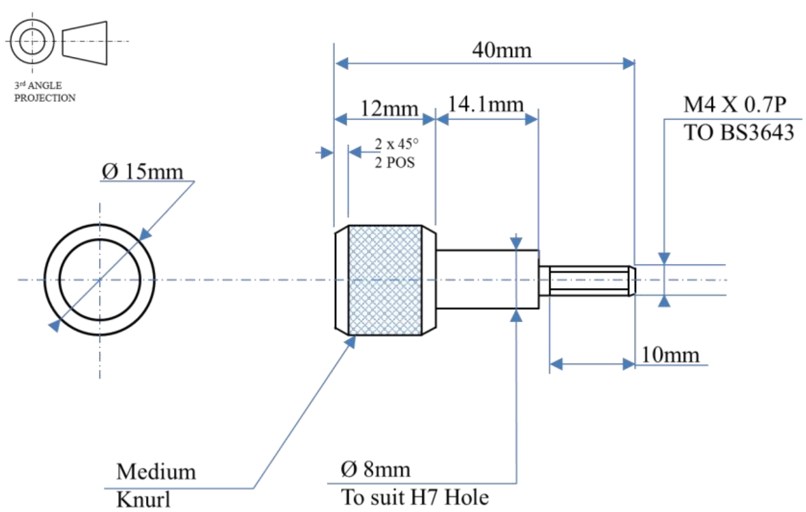


Figure 66: Threaded datum pin concept. For visualisation purposes only to demonstrate use of embedded datums for structure alignment and measurement.

6.9. Step 13 (DfV): Optimise Instrument Plans and Algorithms for Process Control and Uncertainty Reduction

(See A5 in Section 2.5.1)

The current laser tracker measurement process was analysed during the baseline mapping stage as shown in Figure 46. The existing measurement plan was processed with a pattern searching algorithm that minimised the in-process measurement uncertainty by optimising the positions of the laser tracker measurement stations. The results revealed that through optimising the station positions for laser tracker measurement, the uncertainty magnitude could be significantly reduced from an RMS of approximately 0.1mm to 0.02mm.

Prior to tool setting, laser tracker alignment is a fundamental process. Through reducing the uncertainty of the reference network and hence aligning the laser tracker with more precision, the subsequent processes of tool setting and verification are achieved with a greater degree of confidence.

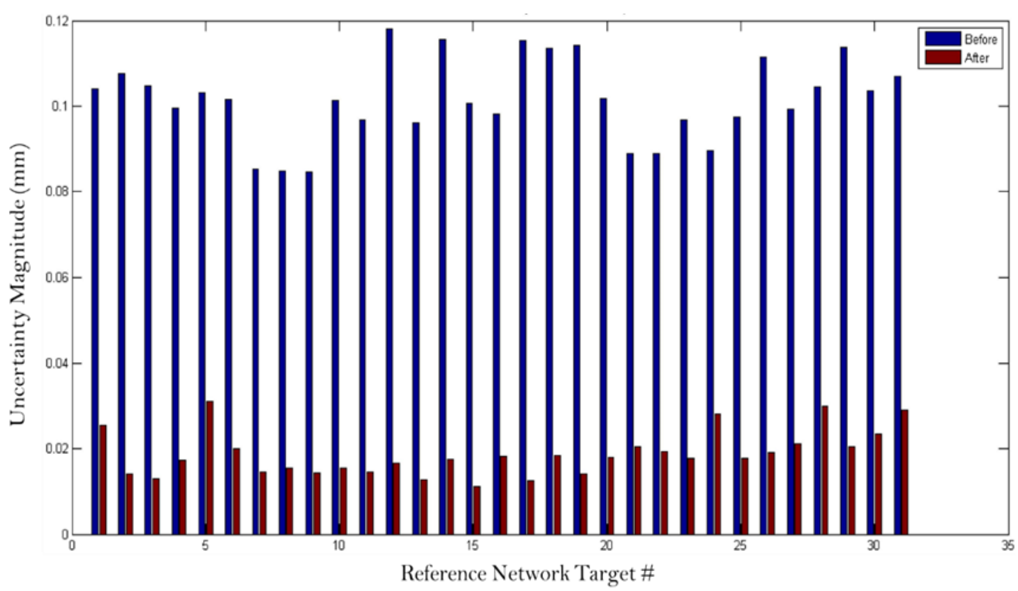


Figure 67: SML1 In-Process Measurement Uncertainty Reduction Through Laser Tracker Measurement Station Position Optimisation Based on the NPL Laser Tracker Simulator [51], [61].

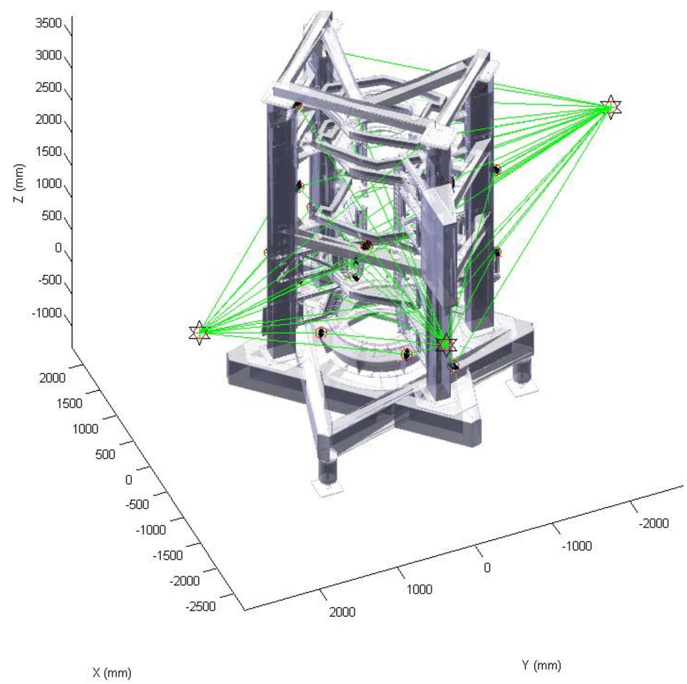


Figure 68: Optimised laser tracker positions (stars) for SML1 assembly.

6.9.1. Question A (DfV): Are all the DfX Criteria Met?

After following the DfV guidelines, the designer is led back to the first question to query the impact of the design changes or proposals upon the overarching DfX parameters. This question was answered through a design review with ADS which led to the selection of technologies to take forward for further development and demonstration. Table 22 shows the technologies selected within the process for further investigation. This forms a critical aspect within the DfV guidelines as multiple inputs are required from DfA, DfM and wider DfX limitations to produce an optimised product and process.

Table 22: Selection criteria and results from multi-disciplinary design team review following Step 12 of DfV in collaboration with ADS.

DfV: Highlighted Area for Further Development		Test Method		
	Build Approach	**UoB Demonstrator**	**ADS Offline**	**Other Offline**
Photogrammetry – usability and accuracy for rapid verification	1, 2-1, 2-2	X	X	
Use of modular tooling for large structures	1, 2-1, 2-2	X		
Use of rotary tables in assembly	2-1	X		
The use of CFRP beams and the associated clamping methods	2-1, 2-2			Uncertainty analysis
The use of zero-point clamps – accuracy and repeatability to be demonstrated	2-1, 2-2	X		
The effect of environment within assembly	1, 2-1, 2-2		X	
The use of in-built Metrology datum's in hardware	1, 2-1, 2-2	X		
Software scripting for enhanced verification	1, 2-1, 2-2	X	X	
Part to part assembly philosophy	1	X		

The areas selected for development and demonstration are listed within the University of Bath Demonstrator column. The technology demonstrator is detailed within the following chapter.

Chapter 7

DfV Technology Demonstrator

In the previous chapter, proposals to improve the E3000 baseline assembly procedure, defined in Chapter 5, were made through applying the DfV guidelines. In this chapter, the elements identified through a multi-disciplinary design review after following the DfV guidelines, listed in Table 22, are implemented and tested. To evidence the effectiveness of applying DfV, a service module spacecraft-like structure was designed based upon available hardware to demonstrate practically the outcome of following the DfV guidelines and test the proposals. The overarching aim of the demonstrator was to prove the benefits and test novel ideas and approaches for spacecraft assembly that are derived from applying the DfV guidelines.

The following section details the decision, design and build process, showing the results that were achieved along with the novel approaches that were created through following the DfV guidelines. The approach was limited by the hardware that was available, nonetheless the results obtained were realistic and significant and have led to full scale implementation within ADS.

7.1. The Technology Demonstrator Introduction

Whilst the design of the technology demonstrator followed general best practice principles with respect to DfM and DfA, the sole purpose of the demonstrator was to demonstrate the advantages of applying the DfV guidelines and showing the benefits that derive from designing the structure and tooling from a large volume metrology based perspective. For this reason, little detail is given with respect to well established DfX principles as these concepts were not required for demonstrating the DfV framework. The available E3000 components for the technology demonstrator are detailed in the following list and further described in later sections (all other parts were designed bespoke for the demonstrator to implement the DfV proposals):

- 2 carbon fibre cylinder skins
- 1 complete CFRP lower cylinder assembly
- Aluminium T-cleats
- 2 lower X shear wall panels
- 1 SM shear wall

7.2. Technology Demonstrator Design

This section describes the elements that were identified through following the DfV guidelines (see Table 22) and describes how they were designed into the technology demonstrator (see Table 23). The following sections further explain how the demonstration of these elements was accomplished.

Table 23: Summary of elements identified through following the DfV guidelines and a brief overview of how they were tested within the technology demonstrator.

Highlighted Area for Further Development	Test Method Summary
DfV enabled part to part assembly philosophy	Demonstrator designed with three SM cylinders and three SM panels for direct part to part assembly utilising embedded assembly datums
Metrology enhanced use of modular tooling for large structures	Modular tooling designed to enable single station construction of brackets and T-cleats
Use of metrology rotary tables in assembly	Rotary table embedded within tooling to reduce redundancy
The use of zero-point clamps – accuracy and repeatability to be demonstrated	Zero-point clamps integrated into tooling base to demonstrate plug and play tooling concept
The use of in-built metrology datum's within the assembly flow chain	H7 holes designed into tooling to enable direct measurement with photogrammetry and laser trackers as well as providing key characteristic for and assembly datums.
Design enabled use of photogrammetry for verification	Software developed to enable rapid verification. Photogrammetry comparison against laser tracker
Software scripting for enhanced verification	Automated reporting demonstrated to remove operator error and decreases manual analysis time scales

7.2.1. DfV Enabled Part-to-Part Assembly Philosophy

The adoption of a Type 1 part-to-part assembly method within manufacturing of spacecraft assemblies would be a major shift from the current Type 2 assembly method. The uncertainty analyses within the DfV guidelines under Step 12 (see Sections 6.6, 6.7, 6.8) revealed that the significant source for potential product variation was the effect of the environment. To better control environmental disturbances, a combined Type 1 and Type 2 assembly method [66] (see Section 6.7) was proposed, utilising a sub-assembly approach whereby maintaining tighter tolerances within a smaller volume subject to less thermal variation. This was tested through the design and build of the technology demonstrator. The central structure was designed from three cylinders and the uncertainty budget was calculated to reflect this for the estimation of uncertainty of the final assembly as seen in Table 24, Table 25 and Table 26.

Table 24: List of uncertainty estimation assumptions for technology demonstrator at the University of Bath LIMA laboratory. Temperature variation estimation significantly reduced from NEOSAT assumptions to reflect the environmental conditions of the University laboratory [45], [57], [108], [111].

Assumptions		
Parameter	**Value**	**Units**
Temperature Variation during setting	0.50	Degrees C
Temperature Variation during build	0.50	Degrees C
Assembly Jig Height	1.00	m
Laser Tracker Distance	1.00	m
Laser Tracker Base Uncertainty	15.00	µm
Laser Tracker Uncertainty	6.00	µm/m
Steel CTE	12.00	µm/m/°C
CFRP CTE	6.00	µm/m/°C
Aluminium CTE	24.00	µm/m/°C
Photogrammetry Base Uncertainty	10.00	µm
Photogrammetry Uncertainty/m	10.00	µm/m
Thermal Scaling	90.00	%
Main Assembly Height	1.00	m

Table 25: Uncertainty estimation for setting of technology demonstrator assembly tooling.

Sub-Assembly Fixture Setting - Aluminium					
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertainty**	
Laser Tracker Alignment	9.00	Normal	2.00	4.50	µm
Laser Tracker	21.00	Normal	2.00	10.50	µm
SMR Centering	6.00	Normal	2.00	3.00	µm
Drift Nest Centering	6.00	Normal	2.00	3.00	µm
Tool Setting Tolerance	30.00	Rectangular	1.73	17.32	µm
Thermal Expansion (Compensated)	1.20	Normal	2.00	0.60	µm
			Standard Uncertainty	**21.19**	µm
			Expanded Uncertainty (k=2)	**42.37**	µm

Table 26: Uncertainty estimation for technology demonstrator completed assembly using aluminium fixturing for the sub-assembly construction.

Combination of Sub Assemblies					
Uncertainty Component	**Value**	**Distribution**	**Divisor**	**Standard Uncertainty**	
Build Variation	42.37	Normal	2.00	21.19	µm
Longest Component Stack	3.00	N/A	N/A	N/A	µm
			Standard Uncertainty	**36.70**	µm
			Expanded Uncertainty (k=2)	**73.39**	µm

The fully assembled product that the technology demonstration resulted in is pictured in Figure 69 with each numbered item described in the following sections. The complete assembly process flow for the technology demonstrator is detailed in Figure 71. All major components were assembled as sub-assemblies without the use of external tooling to maintain critical interfaces. The part-to-part proposal created a reduction of labour through minimising assembly tooling required to achieve specification whereby reducing the fixture setting and verification timescales. Where the components that were previously assembled within two Type 2 assembly jigs, SML1 and SML2/3, the technology demonstrator achieved the assembly of all sub-assemblies using the part-to-part methodology without the use of final assembly jigs.

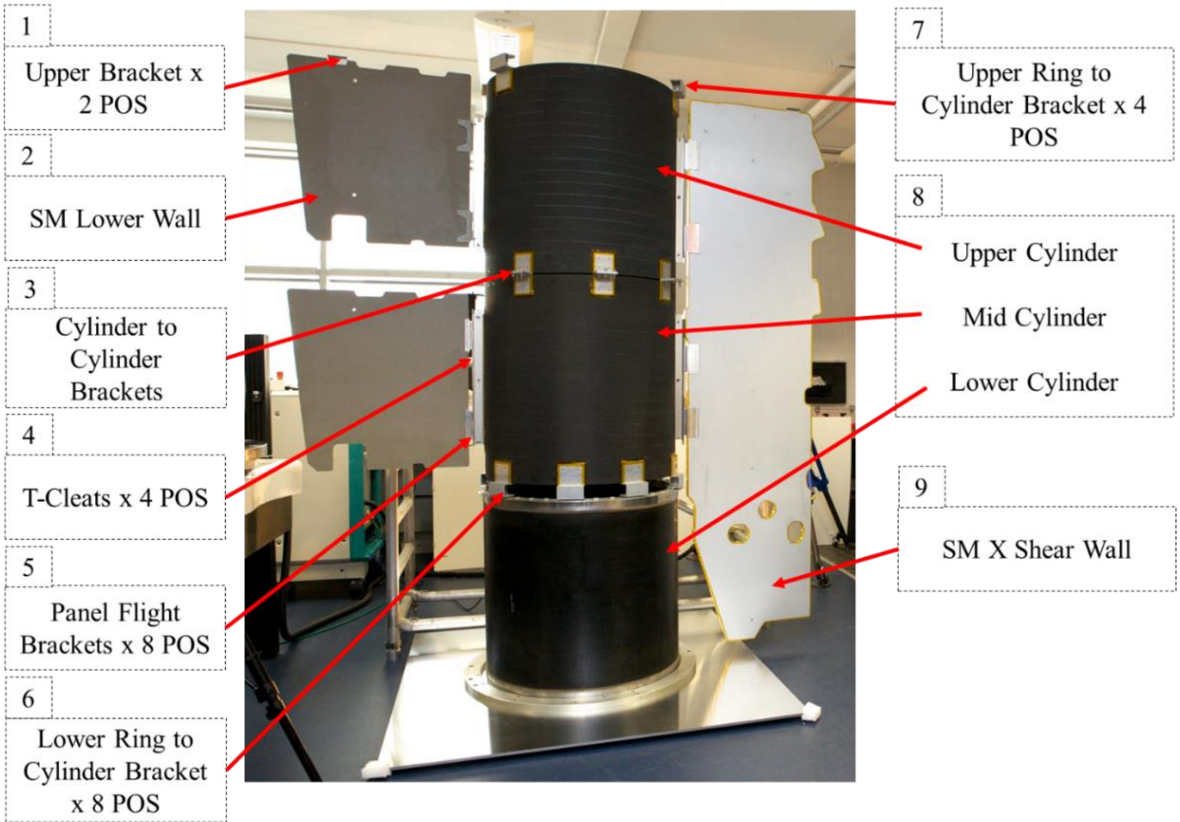


Figure 69: Technology Demonstrator - Fully assembled SM representative structure.

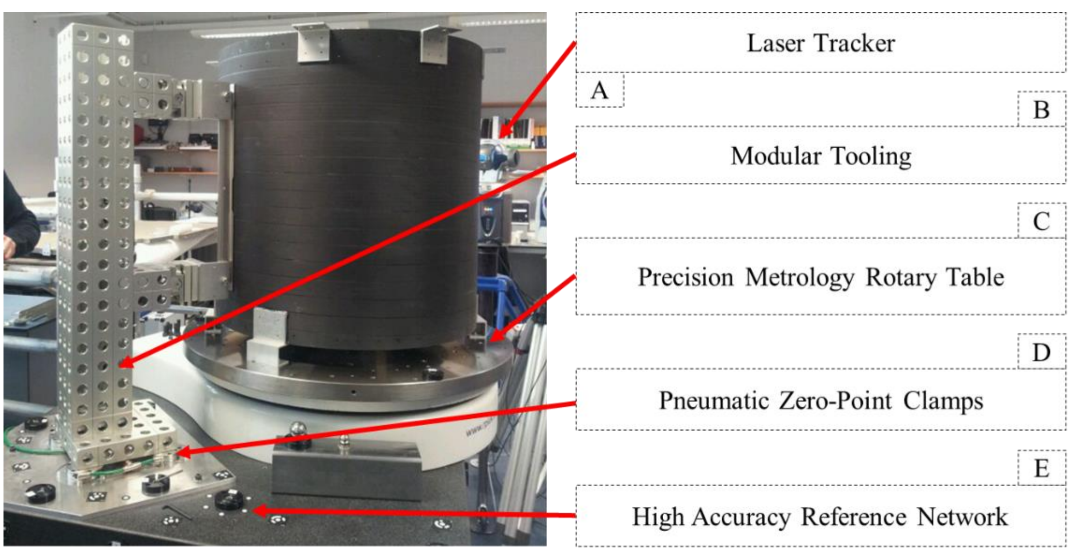


Figure 70: Technology demonstrator assembly tooling located on granite bed.

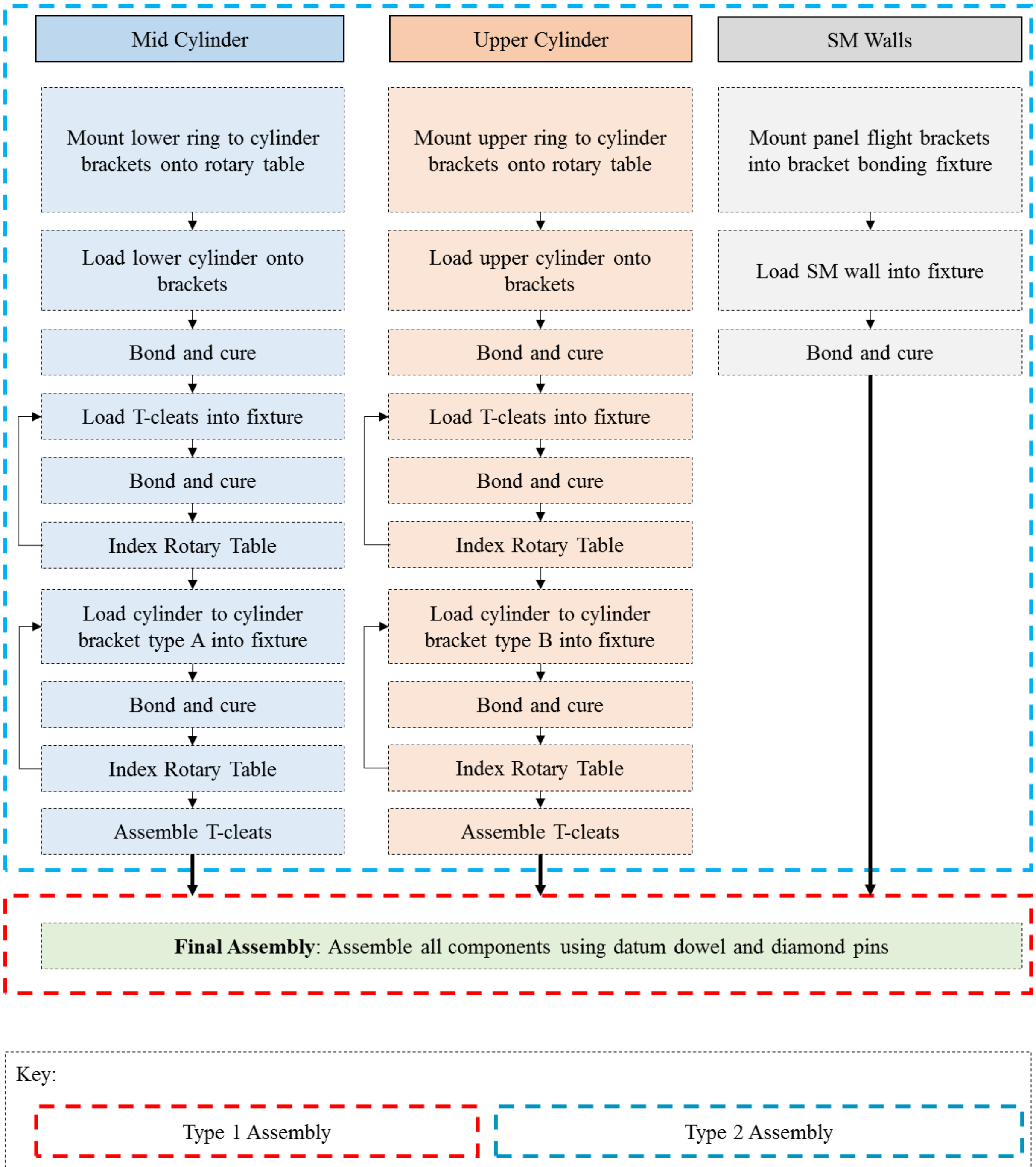


Figure 71: Technology Demonstrator - Assembly process flow.

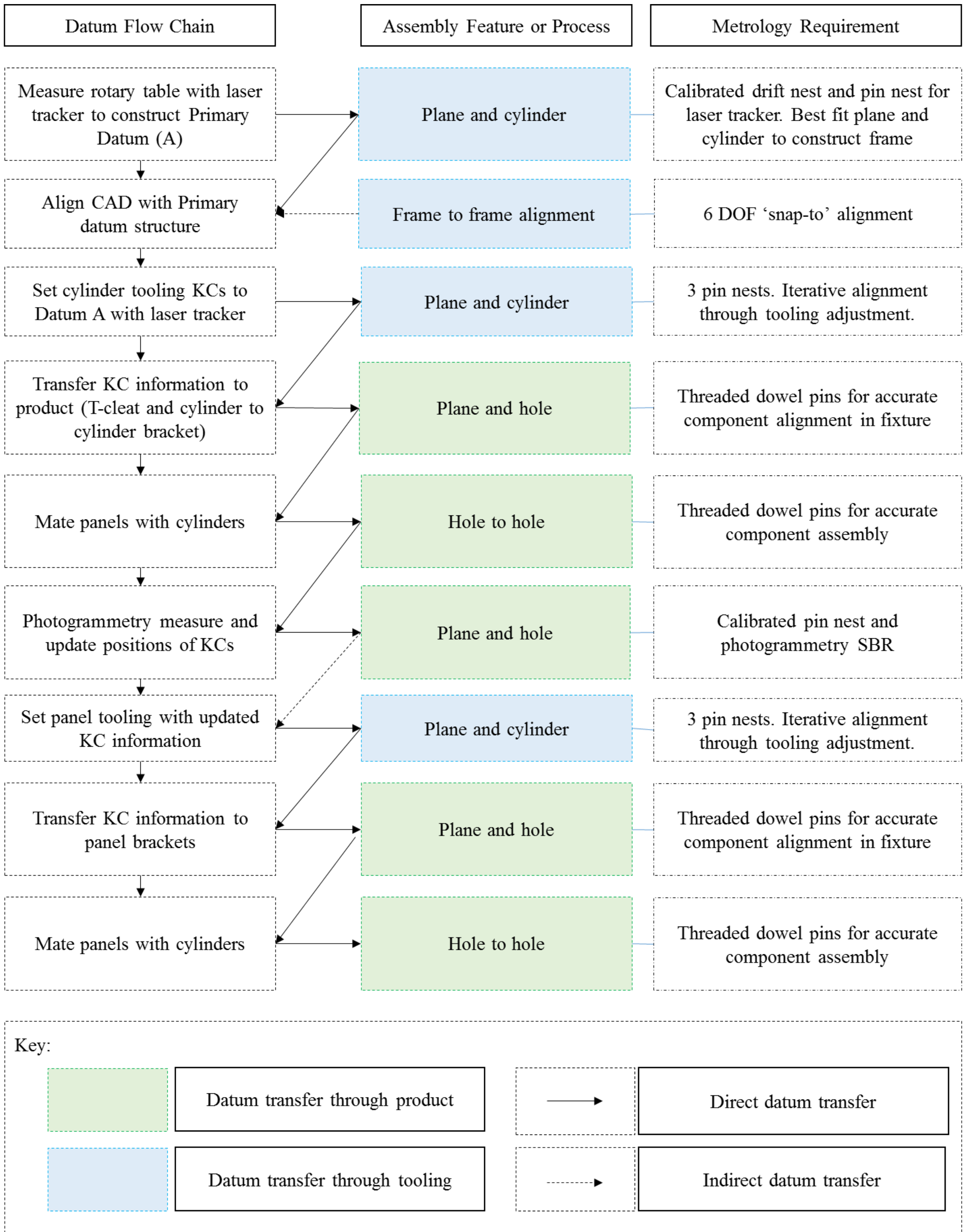


Figure 72: Technology Demonstrator datum flow chain analysis.

The following section describes how the results of DfV were practically applied and tested, making reference to the numbered items in the final assembly construction pictured in Figure 69.

7.2.1.1. Upper Bracket

The Upper Bracket (1) was designed to follow the existing process for panel bracket bonding. A plane is created between the surface of the two upper brackets and the four upper ring-to-cylinder brackets (7). The planarity requirements on the current SM-CM mate is ± 0.05mm. To achieve this, a dedicated bracket bonding tool is craned to the top of the SML2/3 jig and used to locate the brackets as they are bonded to the core structure. This is costly as it requires an additional process step within the bracket bonding procedure that includes laser tracking and tool setting. It also creates additional down-time for the assembly fixture as the brackets cure in-situ. Through the part-to-part assembly method trialled within the technology demonstration, the SM lower wall was brought to the central structure as a complete sub-assembly. The goal of achieving an assembly within tolerance using the part-to-part assembly relied upon the RFT assembly of the panel to the T-cleats that are bonded to the upper cylinder as shown in Figure 73.The location of the upper bracket was verified with the use of a laser tracker that created a plane from 200 measured points between both the upper panel brackets and the upper ring-to-cylinder brackets. The measurement results of the upper plane are shown in Table 27 and agree well with the estimated standard uncertainty previously calculated in Table 26 of ±0.037mm.

Table 27: Upper plane measurement deviation values - The measurement of the upper plane provides evidence of the successful assembly of the SM Walls to the cylinders. The RMS value of 0.013mm is within the existing ± 0.05mm tolerance and the maximum measured deviation.

DEVIATION STATS	
Mean = -0.000000	RMS = 0.013085 Millimeters
Magnitude	
|Max| = 0.031847	|Min| = 0.000006 Millimeters

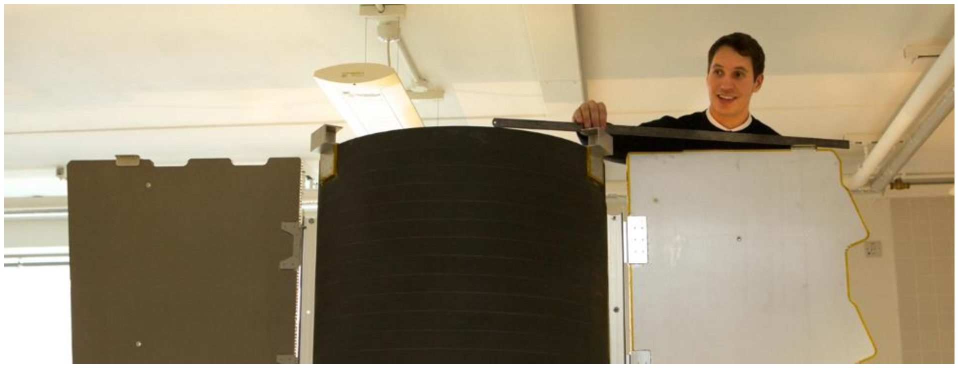


Figure 73: Upper brackets planarity evidenced with steel rule alongside laser tracker measurements. Part-to-part assembly successfully achieved, evidenced by flatness and parallelism of upper brackets = RMS of 0.013mm.

The upper plane measurements were within one standard deviation of the estimated assembly uncertainty detailed within Table 26 proving the benefits of the assembly proposal and evidencing the viability of the approach.

7.2.1.2. SM Lower Wall and SM X Shear Wall

The SM Lower Wall and X Shear Wall were sub-assembled within a modular, reconfigurable bracket bonding jig. The bracket bonding jig was designed such that it could be reconfigured for any panel variant as illustrated in Figure 75. The current method for bracket bonding uses picture frame style steel welded jigs, bespoke for each panel. The reconfigurable fixture used for bonding the brackets onto the SM lower wall was also used to bond the brackets onto the SM X Shear Wall (9). The brackets that interfaced with the T-cleats were designed so that they could be used for part-to-part assembly. The brackets were designed with 6.9mm H7 THRU holes that could be used as metrology datum holes during fixturing, verification and assembly. The uppermost hole of the T-cleat bracket within the assembly of the SM Lower Wall was used as the location hole as seen in Figure 74. The evidence of the successful assembly of the brackets onto the walls is the successful assembly of the walls onto the T-cleats and the measured results of the upper plane created by the upper bracket (Table 27).

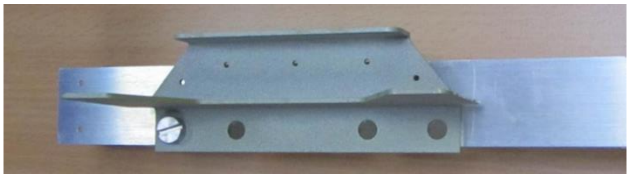


Figure 74: T-cleat and lower wall bracket. Datum pin in position that provides precision location for panel.

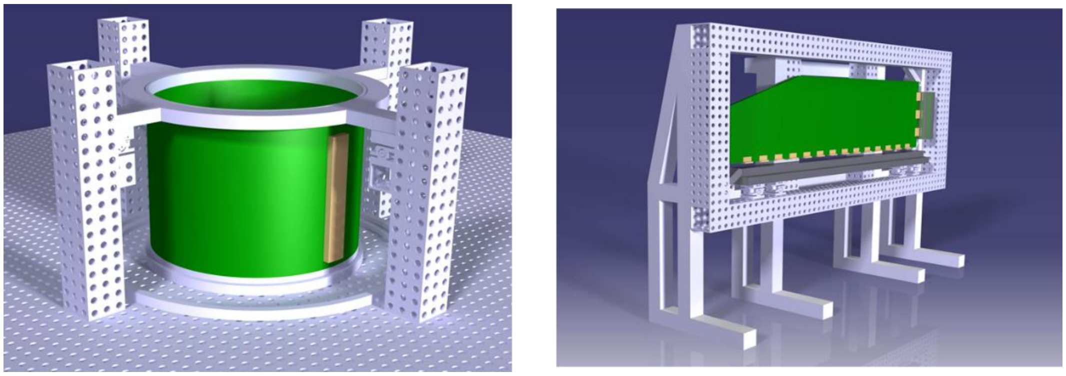


Figure 75: For illustration purposes only - Reconfigurable tooling for bracket bonding procedure. Interfaces reconfigured to enable bracket bonding for all panel variants.

7.2.1.3. Cylinder-to-Cylinder Brackets

The cylinder-to-cylinder brackets were designed to mate the upper and mid cylinders. The design followed the requirement to embed datum features within assembly components to reduce the reliance upon costly fixturing for final assembly and alter the process to suit a Type 1 assembly. The DIA 10 H7 THRU hole was used during assembly for aligning the two cylinders. Precision ground dowel and diamond datum pins were used to ensure accurate alignment and prove the capability of the assembly precision.

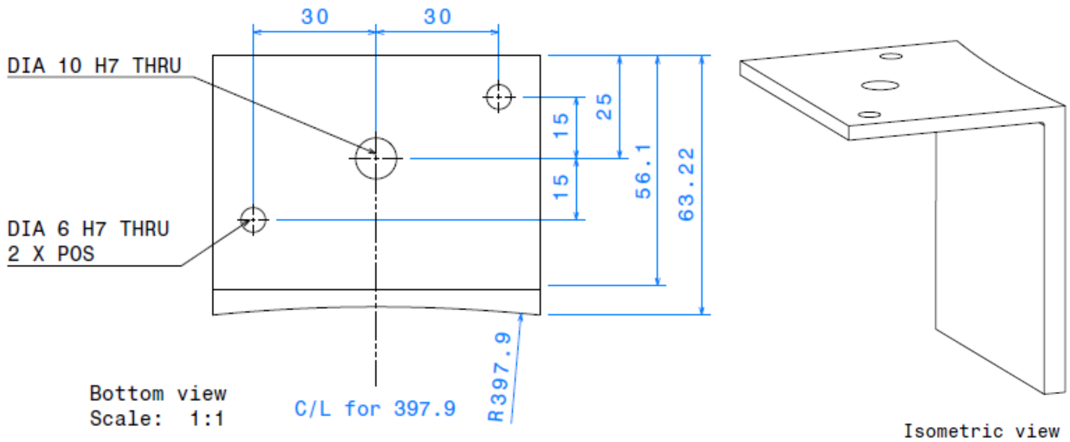


Figure 76: Cylinder-to-cylinder mating bracket drawing extract. 10mm datum hole used for locating upper cylinder onto mid cylinder. 6mm holes provide accurate location holes for fixture alignment during bonding procedure.

The brackets were bonded to the cylinders with a single tool as shown in Figure 77. The DIA 6 H7 THRU holes were used for attachment to the tooling which was directly set and measured with a laser tracker using the same tooling holes, as embedded metrology datums, illustrated within the datum flow chain representation (Figure 72). This enabled a direct transfer of the reference frame within the datum flow chain between the tooling, set with the laser tracker, and the KCs on the cylinder-to-cylinder brackets. This improves upon the current process for the E3000 cylinder assembly as the tooling cradles for the rings are currently set indirectly such that the KCs cannot be measured directly.

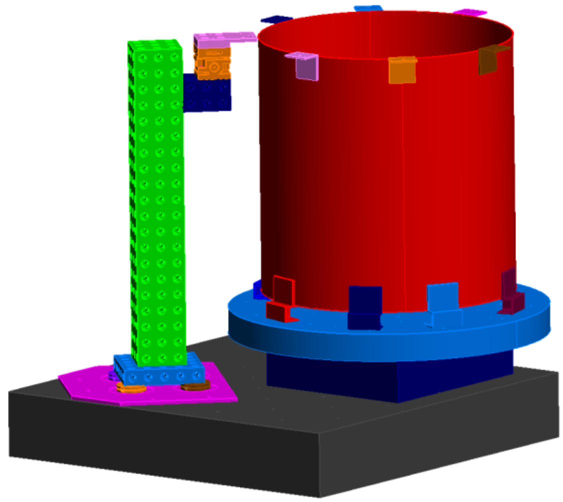


Figure 77: Cylinder-to-cylinder bracket bonding tooling setup. Single tooling structure used to position bracket during bonding procedure.

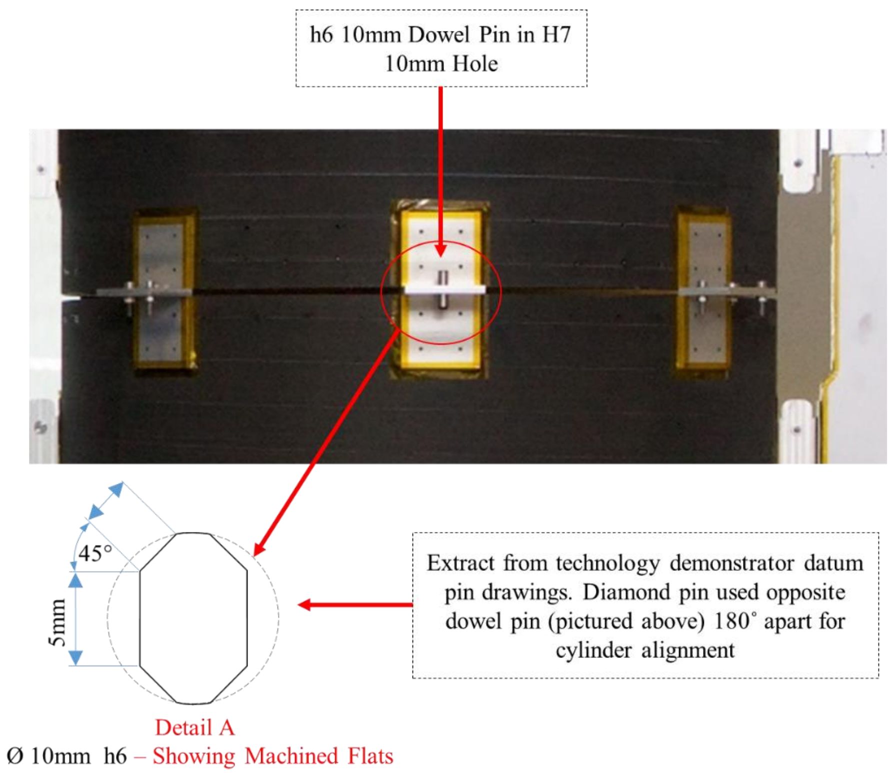


Figure 78: Mid to upper cylinder alignment and assembly using h6 dowel and datum pins within H7 bracket holes. Image showing dowel pin and extract from diamond pin drawing for illustration purposes only.

Figure 79: Cylinder brackets bonding tooling used for all brackets to reduce tooling and improve assembly accuracy through reduced setting variation.

7.2.1.4. T-Cleats

The T-cleats were bonded onto the sides of the CFRP cylinders vertically to provide the attachment points for the SM Lower and Shear Wall brackets. The positioning of the T-cleats was essential for managing the SM upper plane interface so they were designed with embedded metrology datums so that the tooling KCs could be measured and set directly. The datum position on the drawing was critical in the design so that the process accuracy could be focused where required during the machining process as seen within Figure 80 and Figure 81. The T-cleats were positioned and bonded onto the cylinders using the same tooling for each T-cleat. This was designed so that the variation that is built up through multiple tools set with a laser tracker could be reduced to minimise assembly variation as well as tool setting timescales and verification requirements.

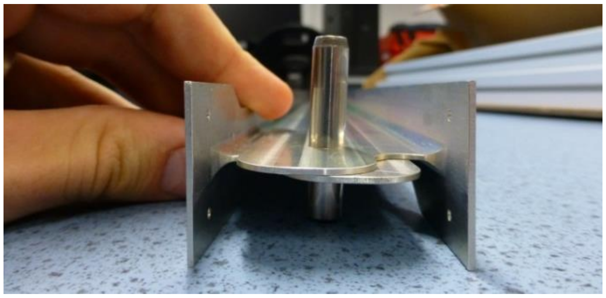


Figure 80: T-Cleat Assembly – Precision location hole used at assembly mating point to control height of critical interfaces between SM cylinder and SM walls.

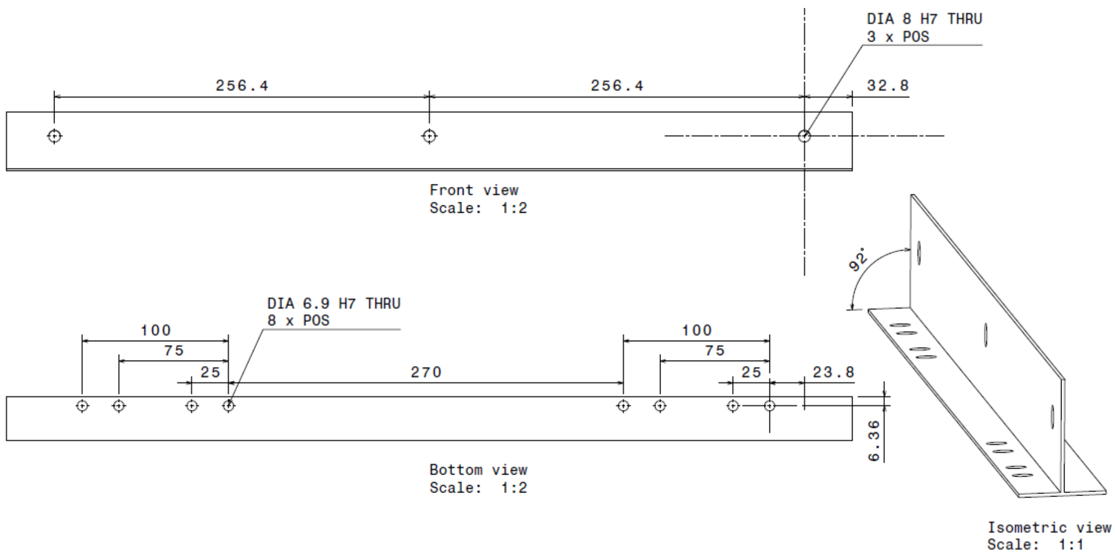


Figure 81: T-cleat drawing extract - dimensions referenced to key assembly features that are also used during alignment to bonding fixture and dimensional verification. The purpose of the design was to enable direct datum flow chain transfer between high accuracy laser tracker network, tooling and assembly components.

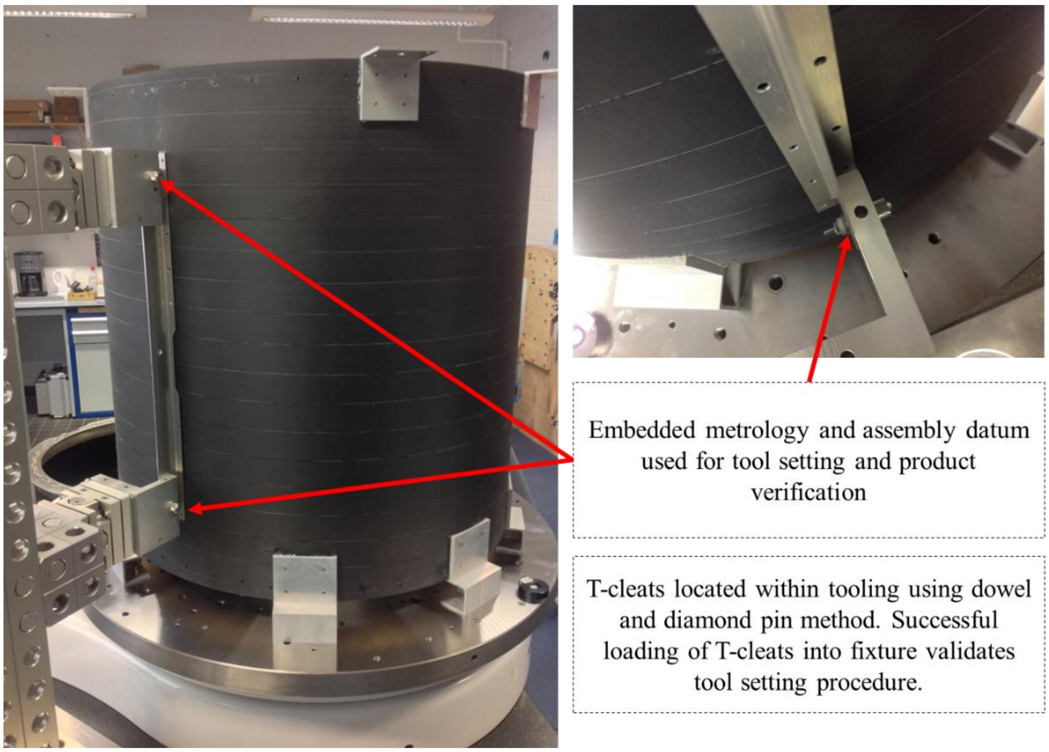


Figure 82: T-cleat tooling and assembly showing use of KCs directly measurable by laser tracker for enhanced verification and tool setting.

7.2.1.5. Panel Flight Brackets

The panel flight brackets were bonded onto the walls and bolted to the T-cleats. The positioning of the flight brackets in relation to the upper brackets provides the SM-CM mate critical interface. The translation of the assembly datums through the build process is critical to ensure that tolerance stacks do not surpass the estimated uncertainty budgets as per Table 21. The part-to-part methodology was applied for the assembly between the flight brackets and the T-cleats such that precision ground dowel pins were used to locate the walls onto the cylinder T-cleats as previously seen in Figure 74. This could only be achieved through directly measuring and setting the KCs within the assembly tooling.

7.2.1.6. Lower and Upper Ring-to-Cylinder Brackets

The lower and upper ring-to-cylinder brackets were designed primarily for mating the mid cylinder with the lower cylinder and providing the plane for which to validate the assembly of the SM walls against respectively. The lower 8 brackets and 4 upper brackets were located using the hole positions shown in Figure 83.

The assembly process utilised a common template for defining the hole positions within the lower and mid cylinders to ensure accurate assembly. The four holes shown in Figure 83 with a PCD of 804.18mm were defined as the KCs for assembly of the lower to mid cylinders. Datum dowel and diamond pins were used to accurately position the mid cylinder on the upper cylinder using the 4 off H7 toleranced holes.

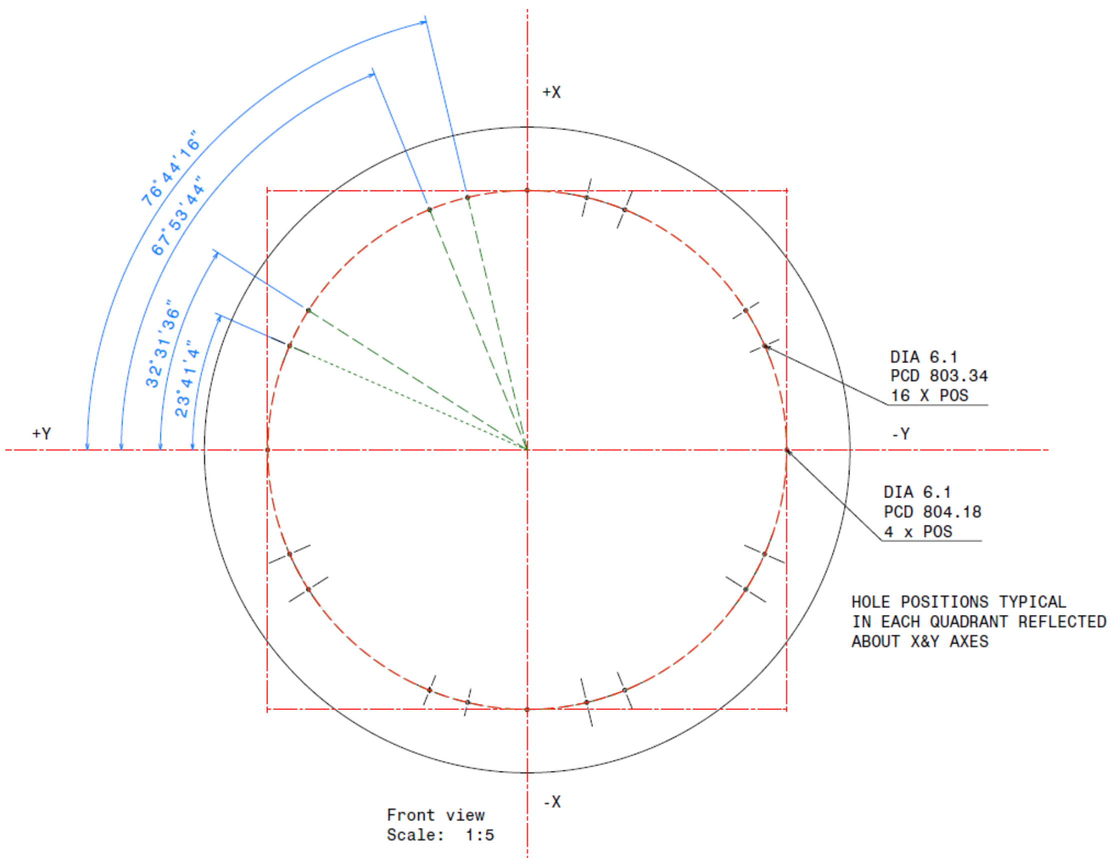


Figure 83: Extract from drawing showing hole positions for mid to lower cylinder brackets during assembly.

7.2.1.7. Lower, Mid and Upper Cylinders

The cylinders were used to provide the scale and geometry for constructing the representative SM structure. T-cleats and brackets were bonded to the cylinders for the assembly interfaces. In order to improve the structural integrity of the 2 carbon fibre cylinder skins, wooden rings were machined to support the top and bottom of the skins and bonded on the inside. The wooden rings were stabilised with struts running vertically along the inside of the skins as seen in Figure 84.

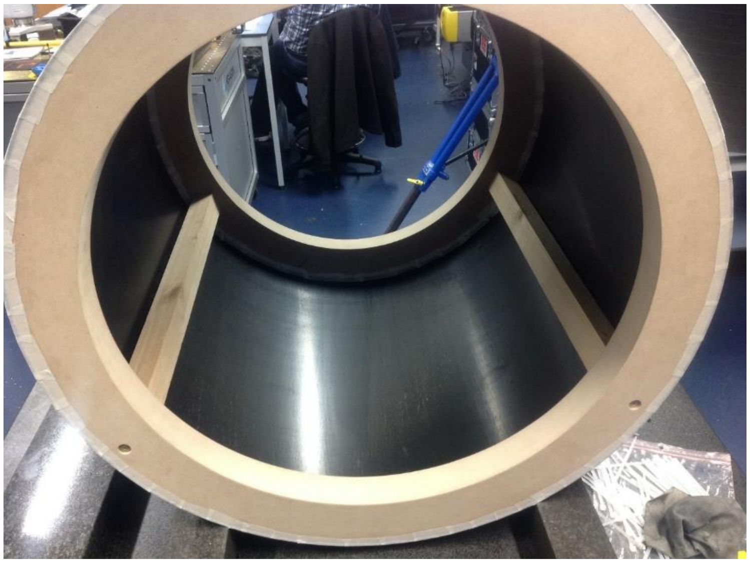


Figure 84: Technology Demonstrator hardware: SML1 CF skins supported with MDF braces.

The available hardware was measured and drawn in CAD so that the assembly model could be designed. The assembly was designed to target the critical interfaces highlighted within the baseline process, previously seen in Figure 48. The critical assembly features for SML1 are prevalent within SM-CM brackets, T-cleat positioning and the SM-SM and SM-CM rings. The cylinders constrained the height to which the technology demonstrator could be designed and defined the overall width of the final product.

7.2.2. Use of Modular Tooling and Zero-Point Clamps for Large Structures

As within the proposed part-to-part assembly philosophy, modular tooling offers increased flexibility for spacecraft variant design. Where the E3000 variants were significantly limited within design change due to the limitations of the assembly jigs, the part-to-part assembly tooling concept presented a larger potential for structural design change. The tooling used within the technology demonstrator design has had previous exposure within the automotive industry, but has yet to be utilised within the spacecraft manufacturing industry, due to the scale and volume over which spacecraft are built [110], [113]. The modular tooling was designed with additional flexibility through the integration of zero-point clamps. The plug and play aspect of the tooling was validated through laser tracker monitoring as illustrated in Figure 85. The zero-point clamps provided a repeatable location for the plug and play tooling with a manufacturer's stated repeatability of ± 0.005mm [114].

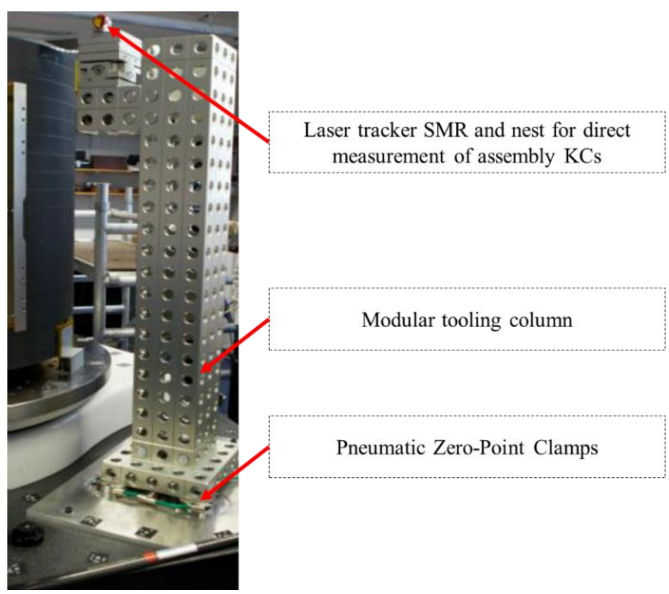


Figure 85: Modular tooling for large structures, use of zero-point clamps to provide plug and play capability with laser tracker SMR used for tool setting and validation.

The pneumatic clamps were designed to enable a plug and play aspect to the tooling. The high repeatability and holding force of the clamps made them a suitable option for providing the foundation to the reconfigurable tooling.

7.2.3. Use of Metrology Rotary Tables in Assembly

The use of the metrology rotary table within the assembly process offered numerous benefits. Through the direct integration of a metrology instrument into assembly hardware, the tooling could be significantly reduced from the existing designs. Reconfiguring the spacecraft structure for the bonding of T-cleats and cylinder brackets could be achieved without the need for external verification as it was contained directly within the tooling through the integrated rotary table. The alignment of the rotary table within the laser tracker reference network was within ± 0.008mm which provided the accurate foundation for building the SM representative structure on. The use of the rotary table was validated through part-to-part assembly construction. Using the h6 toleranced dowel and diamond pins to assemble the SM Shear Wall to the mid and upper cylinder directly tested the accuracy of the rotary table positioning. The rotary table was further tested in order to establish a quantified uncertainty for the indexing of the rotary table within assembly and verification [111].

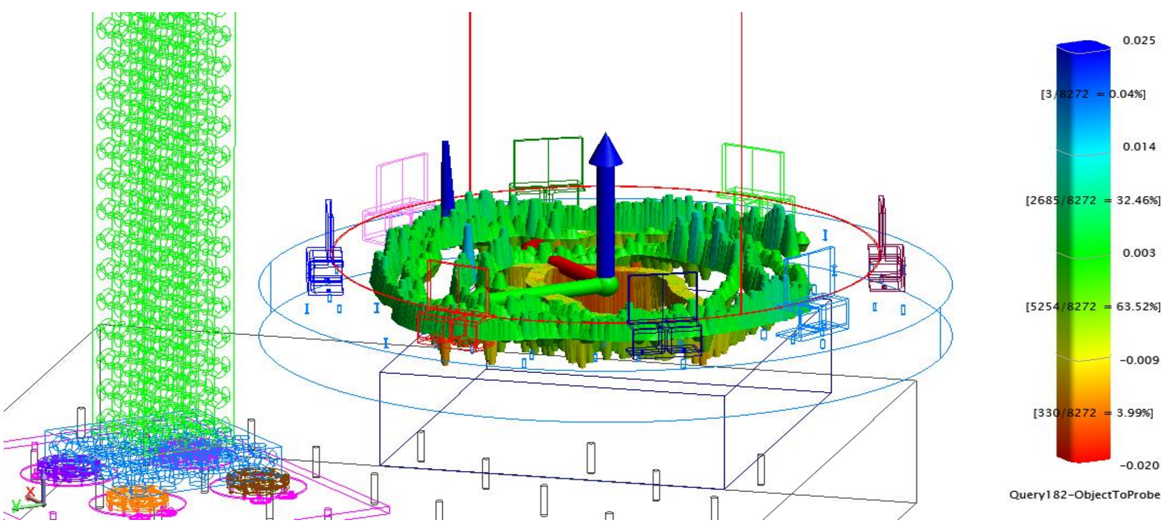


Figure 86: CAD and vector plot of metrology rotary table integrated into assembly tooling to reduce tooling set up and verification labour. Measurement datum constructed at centre of rotary table and verified with laser tracker to be within ± 0.008mm of nominal CAD geometry [115].

7.2.4. Use of In-Built Metrology Datums in Hardware and Photogrammetry

To reduce assembly variation, a concept was proposed to embed metrology features that could be directly set into nominal position through the use of the laser tracker and then transferred directly to the structure as an assembly KC. This was achieved through the design and use of threaded datum pins. Each of the tooling interface plates were designed with a KC directly measurable by photogrammetry and laser tracker metrology systems. The mating T-cleat was measured directly with photogrammetry to verify the assembly prior to mounting the SM walls onto the central structure. The KCs measured on the T-cleats were DIA 6.9 H7 holes that were used to update the positions of the brackets on the SM X Shear wall utilising the flexibility of the fixturing through the use of photogrammetry. This method was repeated for the cylinder-to-cylinder brackets.

In order to locate the tooling accurately, a high accuracy reference network was created that could be measured by both photogrammetry and laser tracker systems directly. The network was created from an optimised five station network which resulted in a network RMS of 0.009mm. This was validated through the alignment with the photogrammetry measurement which resulted in a reference network alignment RMS of 0.011mm.

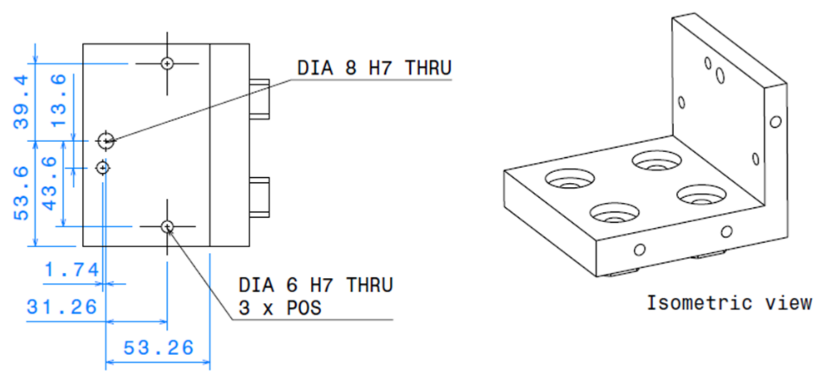


Figure 87: Extract from drawing of T-cleat tooling interface plate. DIA 8 H7 THRU hole used to measure with laser tracker and hold T-cleat during bonding procedure. The same hole used as assembly KC as shown in Figure 80.

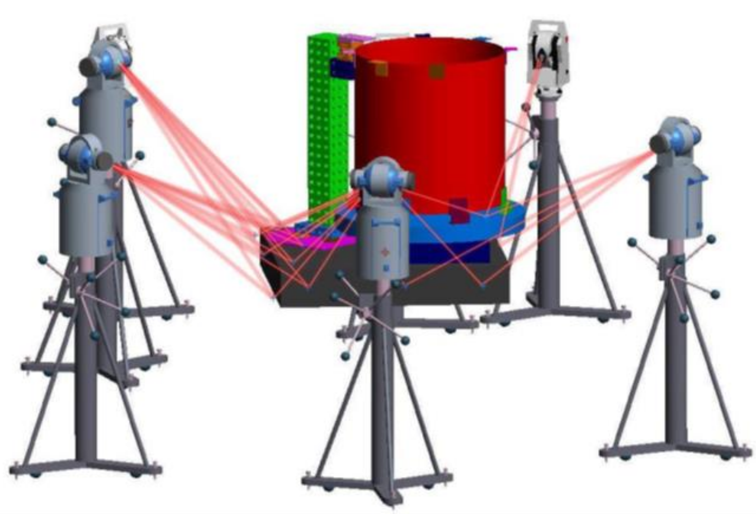


Figure 88: Laser tracker high accuracy reference network. Measurement network created for assembly tooling and structure verification with an RMS of 0.009mm aided through five station measurements as illustrated.

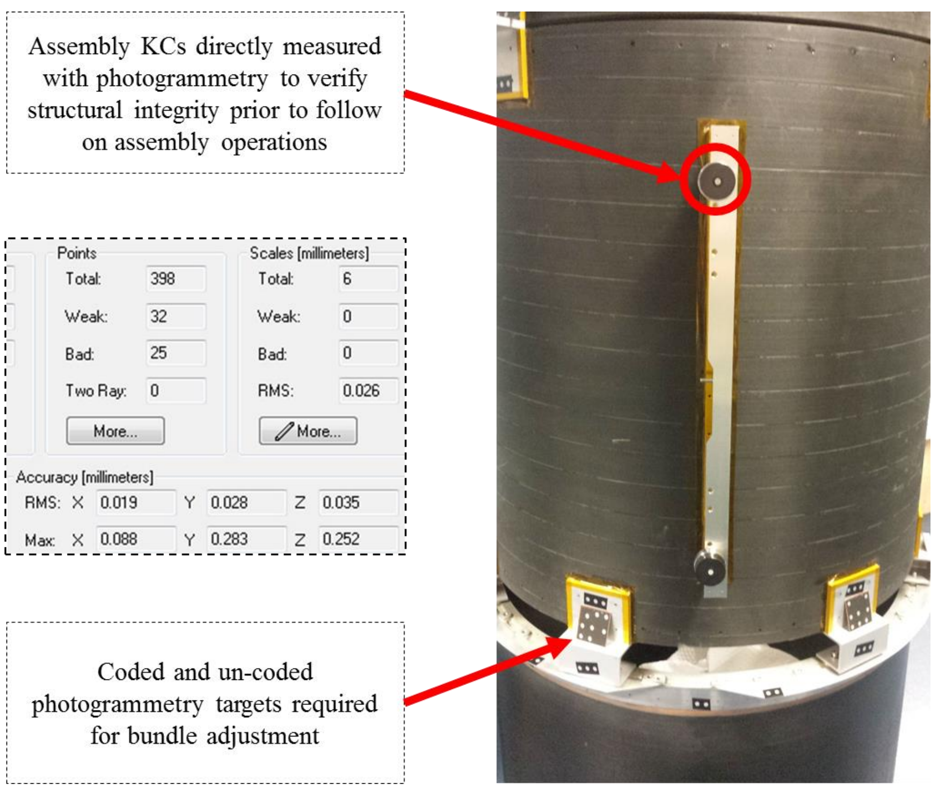


Figure 89: Photogrammetry results for direct measurement of KCs. Facility tooling used to locate photogrammetry targets within T-cleat KCs for follow on assembly processes.

To improve upon the usability of the photogrammetry system for verification, software to automate the alignment and analysis of the raw measurement data was created, screenshots shown in Figure 90. Through trials, this resulted in a reduction of verification analysis timescales from 5 hours to 2 minutes. This was only possible through the design of embedded metrology datums suitable for combined laser tracker and photogrammetry measurement.

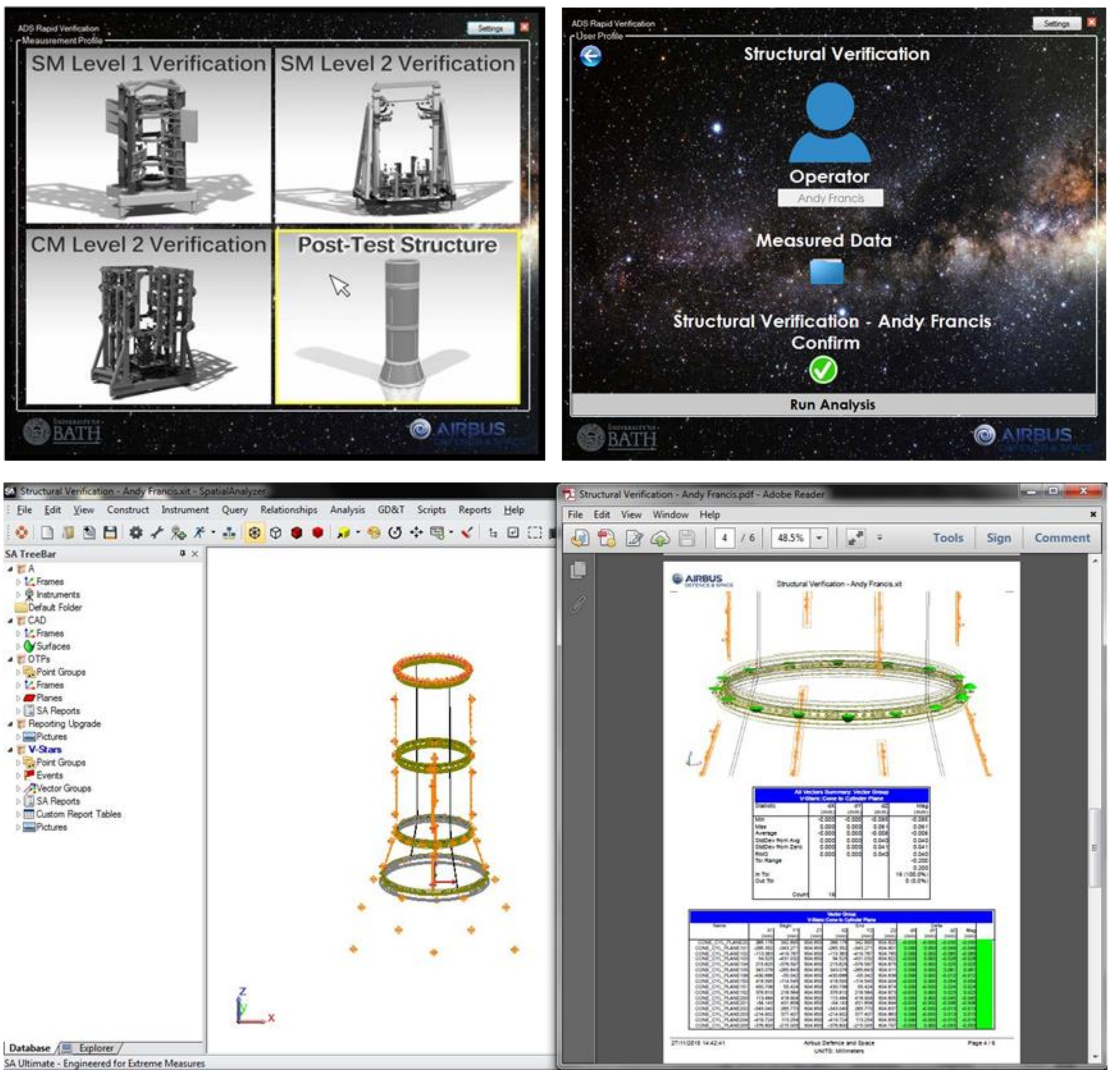


Figure 90: Screen capture for illustration purposes. Bespoke automated photogrammetry measurements analysis software tool for rapid recertification and verification.

7.3. Technology Demonstrator Summary

Through the implementation of the DfV guidelines, the NEOSAT design was assessed from a metrology based perspective, previously described in Chapter 6. This led to the proposal of assembly concepts, novel to the aerospace industry. The concepts were passed through a design team at ADS and potential options were taken forward for demonstration as detailed in Table 23. The technology demonstrator was designed for the sole purpose of testing the concepts proposed through the implementation of the DfV guidelines and subsequent design reviews to validate their viability for spacecraft manufacture.

The estimated standard uncertainty for the final assembly of technology demonstrator SM representative structure was calculated as ±0.037mm, as seen in Table 26. The technology demonstrator was then built and assembled. Measurements were taken of the final assembly, which validated the estimated uncertainty budget. The measurement results of the final assembly showed an RMS value of 0.013mm and max error of +0.032mm when compared to CAD nominal.

This also proved the capability of the proposed part-to-part assembly method. To verify the accuracy of the estimated standard uncertainty, further trials would need to be undertaken. This was not possible within the budget constraints for this research package. The RFT assembly achieved through the technology demonstrator validated the part-to-part philosophy made possible through the use of embedded metrology datums. The use of the embedded metrology datums was critical and only possible through the design of bespoke facility tooling to enable photogrammetry and laser tracker measurements to be combined within a unified spatial metrology network.

The experiments on the proposed concepts, completed during the technology demonstration phase of this research package, evidenced the viability of DfV for use within spacecraft production, which was further validated through detailed trials on an SML1 structure at ADS Stevenage.

Chapter 8

Discussion

In the following chapter, the DfV framework creation is first discussed followed by an analysis of the solution and implementation against the defined aims and objectives as detailed in Chapter 1. The overarching research aim was realised through industrial collaborations and verified through a literature review which led to the identification of a gap within the design domain relating to the consideration of large volume metrology uncertainty and measurement planning during aerospace structure design. Through a thorough understanding of large volume metrology technologies and techniques, a set of guidelines has been created to assist designers in meeting pre-defined objectives for the consideration of measurement uncertainty during early stage design. A process flow was created as a method for communicating the DfV guidelines in an accessible manner to ensure they could be applied practically.

A thorough literature review, supplemented by state of the art industrial scenarios led to the creation of the DfV framework. The proposed framework followed the DfX model (PARIX), that was previously created by Huang et al. [31], to ensure a standardised format between DfX guidelines. This allows the framework to be readily integrated into existing design process flows for successful adoption by industry. The DfV principles created are as follows:

- Constrain product design by the practical and physical limitations imposed by the metrology instrument used for dimensional verification.
- Constrain assembly tooling design by the practical and physical limitations imposed by the metrology instrument used for dimensional verification and jig alignment.
- Use measurement instrument uncertainty models to estimate process assembly uncertainty to aid in the definition and allocation of tolerances for final assemblies during early stage design.

- Optimise tooling design for improved verification and alignment processes based upon measurement instrument use and operation.
- Design factory layout and processes to improve working environment during times of required high accuracy for assembly and measurement requirements.
- Design assembly sequences and verification stages based upon measurement instrument capability.
- Minimise measurement uncertainty through digital measurement planning and optimisation.
- Simulate measurement processes during early stage design to aid in the reduction of LOS challenges whereby optimising the design of assembly tooling.

8.1.1. Design for Verification Guidelines

A set of guidelines for DfV have been proposed, implemented and proved to work (first aim in Section 1.4 and primary research question in Section 1.5). The guidelines were based on techniques proposed in the literature and from experience gained in a number of practical case studies. They were used in a study of assembly processes for a large volume aerospace structure. Use of the guidelines yielded a significant reduction in estimated assembly uncertainty, which was verified through the design and build of a technology demonstrator.

8.1.2. Methods to Assist Designers

The DfV guidelines provide methods to assist designers in defining critical tolerances in large volume assemblies (secondary aim in Section 1.4). More specifically, they help to achieve the following (secondary research question in Section 1.5):

1. Reduced production costs (Section 6.7).
2. Reduced fixture redundancy (Section 6.7).
3. Increased production rates (Section 6.7).
4. Improved product conformance (Sections 6.7 and 6.8).

Furthermore, they also act as an aid to influence the following, as to reduce cost and time whilst improving product quality (tertiary research question in Section 1.5):

1. Assembly processes (Section 6.7).
2. Tooling design (Section 6.7).
3. Tolerancing (Section 6.6).
4. Metrology planning (Sections 6.4, 6.5, 6.9 and 6.9.1).

More specifically, these aspects relate to the objectives identified in Section 1.4, which are discussed in the following sections.

8.1.3. Metrology instrument specific constrained product design.

This relates to Objective 1 in Section 1.4. This step leads the designer to consider methods for verifying the product during and after final assembly. This follows to ensure the designer incorporates features to enable the product to be measured efficiently, based upon the characteristics of the metrology instrument chosen for product verification. Methods were demonstrated within the implementation of DfV to prove the benefits of this step in reducing verification timescales and potential error sources from measurement that cannot adhere to best-practice due to poor design. Product features were explored that allow for seamless transfer of digital datum structures between instrument and product during verification processes. This was proven through the technology demonstrator with the design of features that enabled direct measurement of the product with both laser tracker and photogrammetry technologies, within the same reference frame.

8.1.4. Metrology instrument specific constrained tooling design.

This relates to Objective 2 in Section 1.4. The principles behind this objective are similar to those in Objective 1. The distinction has been made between the product and the assembly tooling as alternative metrology instruments are often used for jig alignment and verification as with product verification. It has also been observed that the product design team are most usually a different team than the tooling design team and so it was deemed necessary to separate the two objectives one from another so that they could be represented separately within the DfV framework.

8.1.5. Measurement uncertainty informed tolerancing.

This relates to Objective 3 in Section 1.4. Principles behind the calculation of measurement uncertainty for large volume metrology instruments were described and demonstrated. Methods were clearly explained for how the results from measurement uncertainty analysis should place constraints upon tolerances for Type 2 assemblies. Dimensional uncertainty was proved to be the dominant factor hindering aerospace structure conformance. Processes were created to direct design engineers through the estimation of assembly uncertainty from a metrology-based perspective to feed into defining realistic tolerances. This led to the optimisation of assembly tooling in order to meet product requirements, evidenced through the technology demonstrator.

8.1.6. Measurement uncertainty constrained assembly tooling design.

This relates to Objective 4 in Section 1.4. Application of the DfV framework led to uncertainty analysis of an existing aerospace assembly process. This revealed the primary sources of potential error within the assembly tooling, which led to a novel assembly approach that minimised disturbances from major sources of variation. Assembly tooling was designed and built to demonstrate the assembly of a representative spacecraft-like structure using the DfV tooling approach. The approach achieved assembly accuracies that exceed the current process and obtained reduced verification timescales with minimal tooling.

8.1.7. Measurement uncertainty constrained process design.

This relates to Objective 5 in Section 1.4. The existing processes during the E3000 assembly were mapped against the factory floor layout and environment. Two key sources of major contributors to measurement uncertainty and dimensional variation were identified within the Andromeda room, where the E3000 s assembled. Within the context of generic application of

DfV, this leads to a proposal for the consideration of the process in a holistic manner when considering all the required interlinking processes required for successful assembly of large volume components. Subsequently, this leads the designer to optimise the production floor layout to improve rates of RFT manufacture through the understanding of the implications of the environment and parallel processes during structural assembly, integration and verification.

8.1.8. Measurement uncertainty guided assembly sequence design.

This relates to Objective 6 in Section 1.4. Aerospace assemblies, including the current E3000, are typically realised through Type 2 assembly methods and tooling approaches. Through the application of the DfV guidelines, it was found that the E3000 could be more accurately assembled within the given working environment, with a greater degree of accuracy using a Type 1 approach. This was due to the increased measurement uncertainty and product variation due to the vertical thermal gradients that were measured within the Andromeda room. Through controlling the sub-assemblies to a greater degree of accuracy and applying the part-to-part assembly method, it was proposed that the final assembly could be successfully achieved with statistically reduced levels of variation. This was successfully proved through the technology demonstrator which incorporated these philosophies into the design and build. The three sub-assembled cylinders were assembled to a high degree of accuracy and assembled together without the aid of external tooling. The assembly of the shear wall panels proved the accuracy of the cylinder sub-assemblies and successfully mated, proving the concept.

8.1.9. Measurement uncertainty guided, verification based design.

This relates to Objective 7 in Section 1.4. Methods for integrating features into products at the design stage to enable enhanced large volume metrology instrument integration were explored. Software for advanced verification was created to demonstrate the benefits of this. Assembly tooling and structural components were designed for direct integration with state-of-the-art metrology systems which led to decreased verification timescales with direct tool setting from actual measurement data to optimise follow-on assembly processes.

Chapter 9

Conclusions and Future Work

In this chapter, conclusions are drawn from the research and future work is proposed. The DfV guidelines were applied to the E3000 spacecraft so that a comparison could be made between an existing assembly process and the assembly process derived through following the guidelines in order to test the robustness of the proposed solution. This led to a design review with a multi-disciplinary design team at ADS where new proposals, introduced through DfV, were critiqued against product requirements and down-selected for further investigation resulting in a technology demonstrator design and build.

Two types of assembly methods are identified in the literature, discussed in 2.3.3.1. Type 1 involves assembling all the piece parts without the use of external tooling to control location. Type 2 involves the use of external tooling to control positions of critical parts and features. The research undertaken in this thesis is primarily concerned with identifying improvements for Type 2 assembly methods. Processes have been proposed to aid in determining when to use a Type 1 or Type 2 assembly method based on large volume measurement uncertainty analysis. This formed the basis for discussions on how to ensure constraints posed by measurement uncertainty with associated impacts upon tolerance allocation should be considered within early stage design. Following on from this, how tooling design is influenced to both meet measurement uncertainty constraints and also enable an optimised measurement solution to ensure capable verification processes was investigated. This translated into discussions and demonstrations of how the results feed into product design optimisation to permit advanced metrology techniques to reduce verification timescales and costs.

9.1. Conclusions

The main principles behind DfMA are based upon part reduction, ease of assembly and manufacture and reduced cost [1]. DfV differs from and compliments DfMA in that it seeks to further optimise the design so that it promotes right-first-time through the consideration of measurement process planning and measurement uncertainty.

As detailed in Chapter 6, through following the DfV framework, three proposals for improvements to the current E3000 design and assembly process were proposed. DfV helped to optimise the product and process as follows:

a) Metrology instrument specific features were designed into both the tooling and structure to improve the measurement process.
b) The assembly process was redesigned to reduce uncertainty in final assembly.
c) The cost of tooling was decreased by minimising the number of interfaces that required setting with a laser tracker.
d) The cost of the metrology process was reduced through integrating features that could be measured directly with an automated system.
e) The cost of the metrology process was reduced through minimising the number of tools that required metrology.
f) Measurement uncertainty was reduced through optimised measurement planning.
g) The design of the tooling incorporated integrated metrology systems (metrology rotary table) to reduce the uncertainty in part assembly.
h) The tooling was improved through the consideration of the uncertainties induced from the environment during assembly processes.
i) The design method aided the integration of rapid metrology techniques so that modular, reconfigurable tooling could be introduced.

The estimated reductions in overall assembly uncertainty were approximately 35%, 50% and 50% for assembly proposals 1, 2-1 and 2-2 respectively by optimising the design for verification purposes.

A technology demonstrator was designed and built to incorporate all of the areas of interest highlighted through the DfV design review process. It incorporated aspects from each of the three proposals for improved assembly. Although not directly comparable, the demonstrator was estimated to have an assembly uncertainty of ± 0.073mm (2σ) which is approximately half of the current baseline process. In fact, when used, the demonstrator achieved assembly errors of less than 0.033mm.

Repeated runs of the full assembly process would be required to gather an assembly accuracy distribution for which to compare the estimated values against. However, one of the key purposes of DfV is to ensure right-first-time assembly of large aerospace components that have not had prior assembly. From this perspective, the demonstration was a success.

9.2. Future Work Recommendations

As noted in Section 7.3, it was only possible to run the technology demonstrator once. This run achieved an assembly error well within the estimated margin proving ability for right-first-time manufacturing within spacecraft assembly through the use of a part-to-part assembly methodology. Clearly it would be preferable to undertake repeated runs using the demonstrator or another appropriate assembly operation. Nonetheless, the results were encouraging and as such, ADS is using the proposals derived from the DfV approach.

9.2.1. Refinement of the DfV Framework

Similar to DfA and DfM, it is assumed that the proposed DfV framework could have much to be improved upon through further testing and implementation. As with DfA and DfM, it is anticipated that the framework will continue to develop and grow over time as it is critiqued and added to by further expertise in the field. The framework will need to be tested by multi-disciplinary design teams across alternative sectors to prove the applicability of the guidelines against various products within differing design environments.

As knowledge within the large volume metrology community increases, instrument uncertainty models will be improved upon leading to additional optimisation techniques, such as the laser tracker position optimisation algorithm [51]. This will lead to increased benefits from the application of DfV as more data can be added to the uncertainty calculations and simulations within the design phase to further optimise the product and process for verification.

9.2.2. Further Case Studies and the Application of DfV in Other Areas.

To further test the robustness of the proposed DfV framework, it will need to be tested against additional products and applications. Whilst the space industry represents an extreme example with respect to demanding tolerances over large volumes and high cost components, there are other industries where this framework would also render significant benefits. Examples include the use of scientific hardware that require high assembly and alignment accuracy over large volumes such as the Large Hadron Collider (LHC) [116]. Other examples include fuselage alignment, wing assembly and wind-turbine manufacture and assembly.

For industry to adopt this approach more readily, the framework needs to be integrated into software tools and developed into a more usable system through further industrial use applications, similar to the evolution of DfA and DfM, which have continually improved and developed since being created.

Commonly used simulation-based tolerancing software currently relies upon user input data to perform tolerance analysis effectively. The integration of large volume metrology instrument uncertainty simulators directly into CAD packages could significantly improve the design experience for tooling engineers, particularly in the aerospace industry. Tolerance allocation and assembly sequencing could be enhanced through the limits defined by measurement uncertainty analysis and so result in optimised assembly processes and design for verification.

Research Outputs Resulting from this Work

A. Francis, P. Maropoulos, G. Mullineux, and P. Keogh, “Design for Verification,” *Procedia CIRP*, vol. 56, pp. 61–66, 2016.

J. Muelaner, A. Francis, M. Chappell, and P. Maropoulos, “A hybrid Measurement Systems Analysis and Uncertainty of Measurement Approach for Industrial Measurement in the Light Controlled Factory,” in *Second International Conference on Sustainable Design and Manufacturing, Seville, Spain, 12-14 April*, 2015.

P. Maropoulos, J E Muelaner, A Francis, “Uncertainty of the Measurement of Radial Runout, Axial Runout and Coning using an Industrial Axi-Symmetric Measurement Machine,” *38 th MATADOR Conference*, *2015.*

A. Francis, P. Maropoulos, Keynote: Design for Verification in the context of the Light Controlled Factory, 2015. *The International Conference on Manufacturing Advanced Composites. Bristol, United Kingdom, 24-25 June, 2015.*

A. Francis, P. Maropoulos, “Design for Verification Keynote Address”, 2015. *Sustainable Design and Manufacturing. Seville, Spain, 12-14 April, 2015.*

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